Highlights from the Telescope Array experiment

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on behalf of the Telescope Array collaboration

22th Lomonosov conference
Moscow, 27.08.2025

Outline

- Ultra-high energy cosmic rays (UHECR): research & problems
- Telescope Array (TA) experiment
- UHECR all-particle energy spectrum
- UHECR mass composition (types of paricles)
- Anisotropy and search for UHECR sources
- UHE gamma-rays and neutrinos

Ultra-high energy cosmic rays

- Protons and nuclei, E > 1 EeV (10^{18} eV)
- HEP parameter space not studied in terrestrial experiments
- Flux is very low ~ 1 $km^{-2}yr^{-1}$
- Only indirect observation (interactions with the atmosphere)
- Origin is unknown (extrtagalactic)

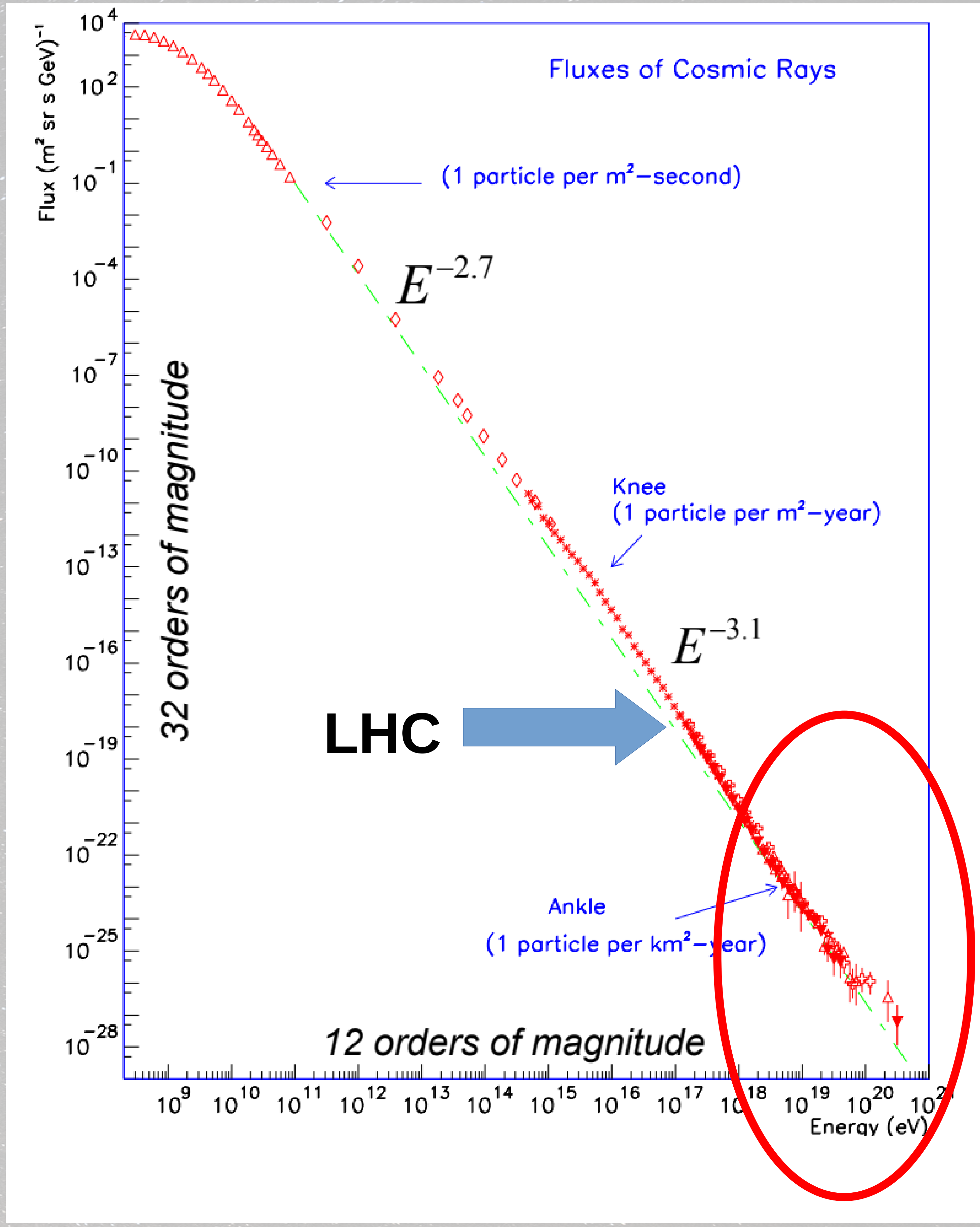
From the list of 30 unsolved physics problems for XXI century

27. Проблема темной материи (скрытой массы) и ее детектирования.

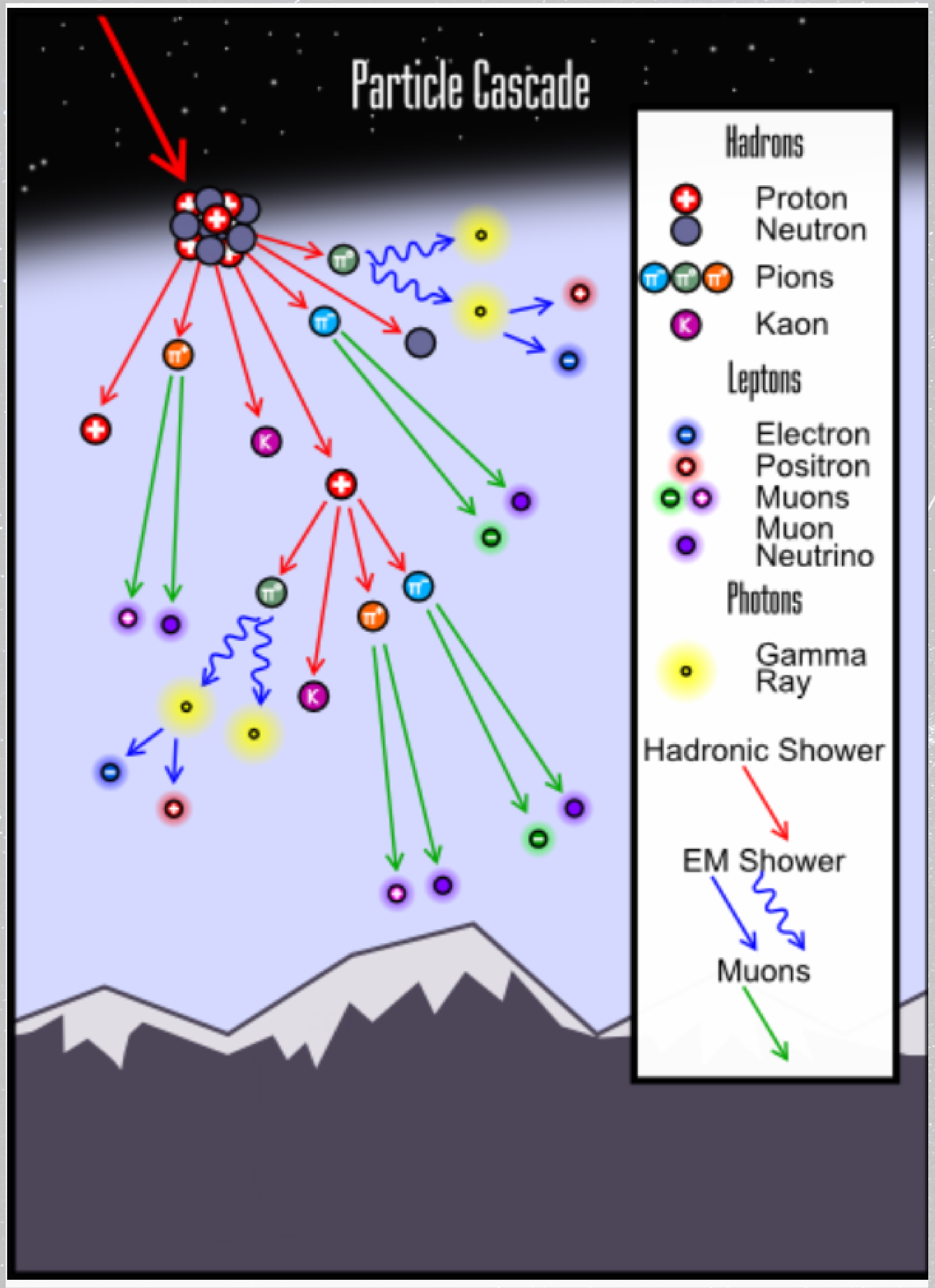
28. Происхождение космических лучей со сверхвысокой энергией.

29. Гамма-всплески. Гиперновые.

V.L. Ginzburg, 2001



Observation of UHECR



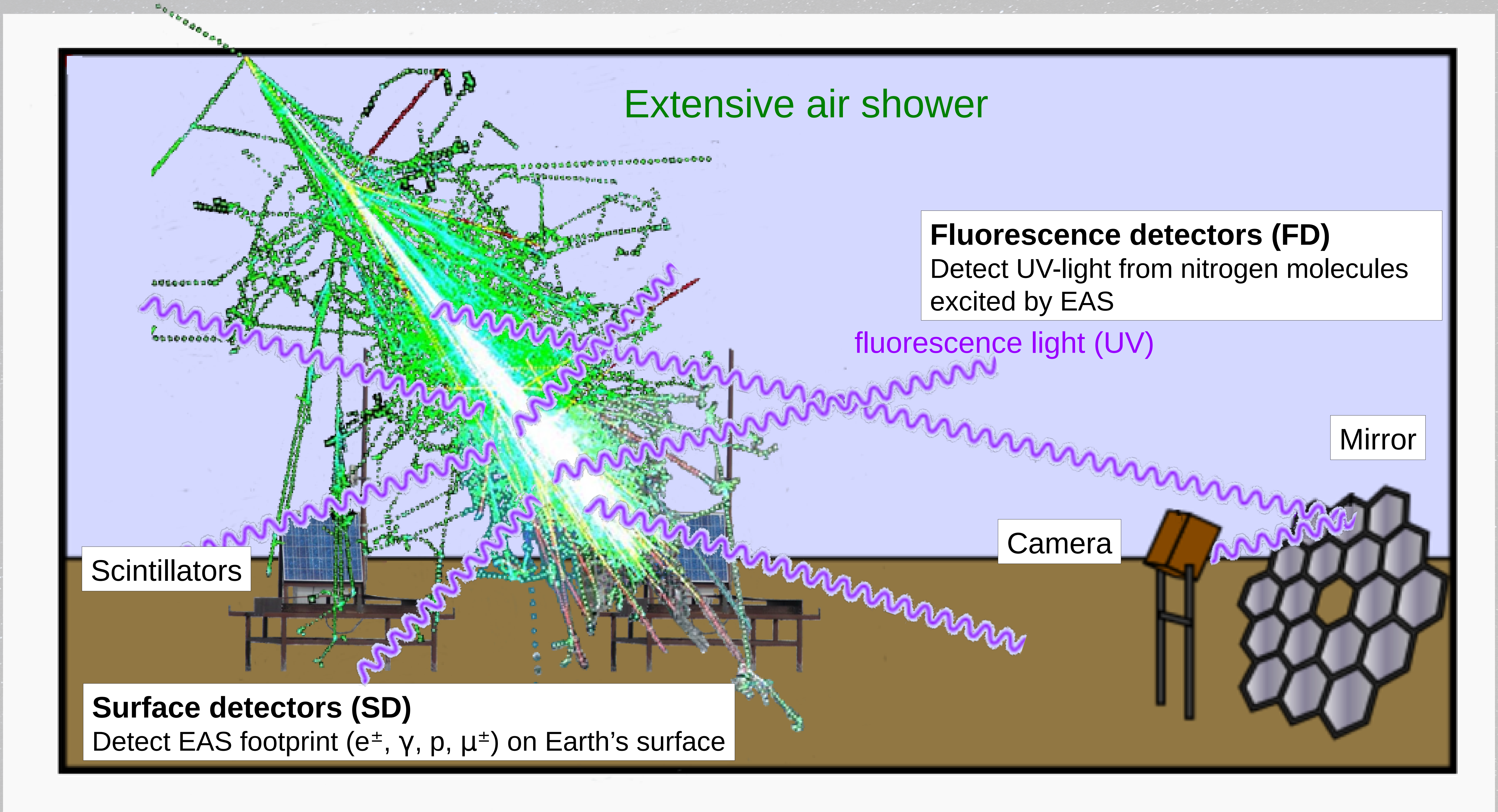
Interaction of cosmic rays in the atmosphere

- Cosmic ray interacts with the atomic nucleus in the upper layers of the Earth's atmosphere (altitude ~ 10 km)
- Collision generate a large number of secondary particles
- Jets of these particles continue to interact with the atmosphere generating a cascade of billions of particles that reaches the Earth's surface

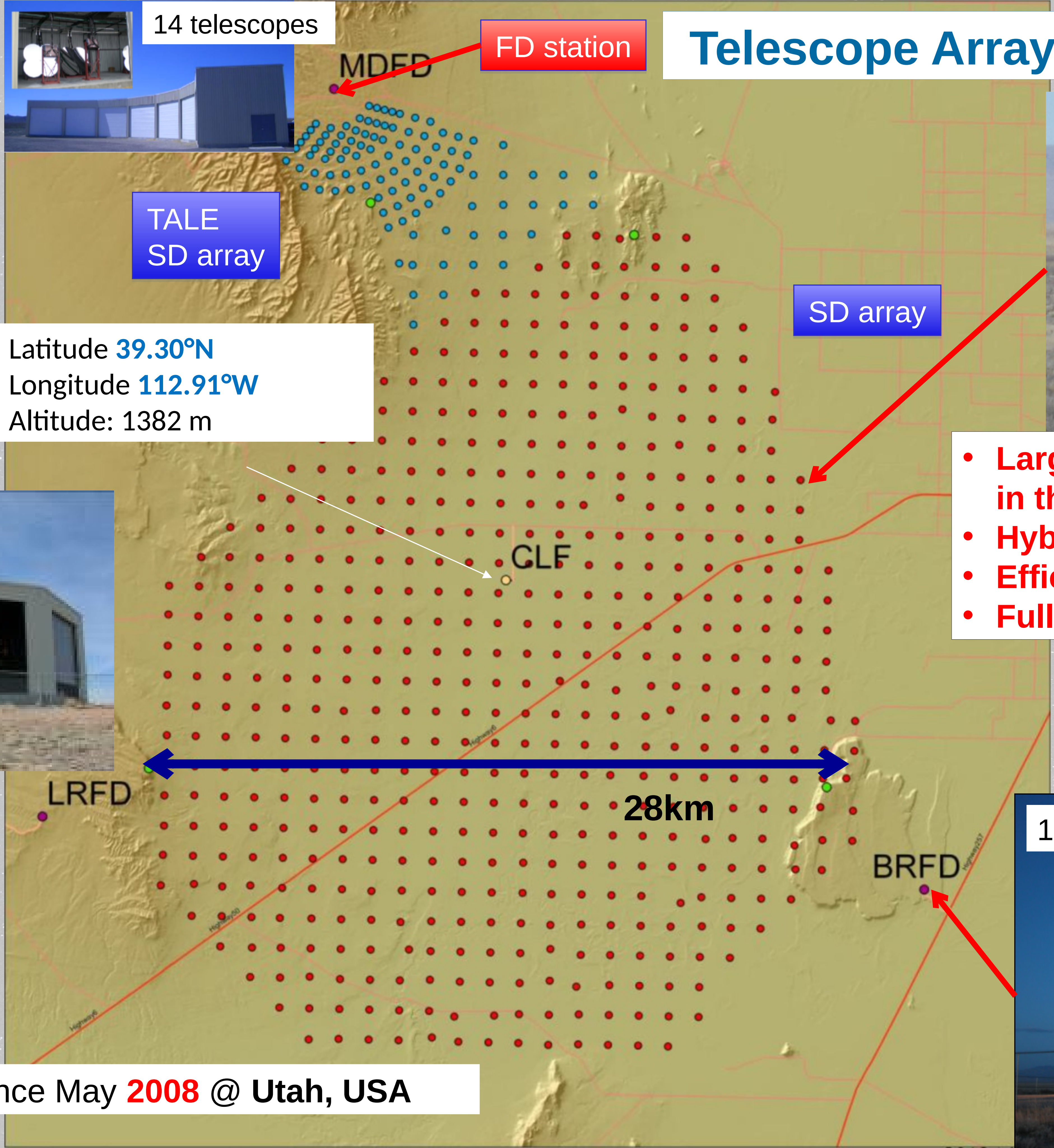
It is an extensive air shower (EAS)

Discovered by Pierre Auger in 1939

Observation of UHECR

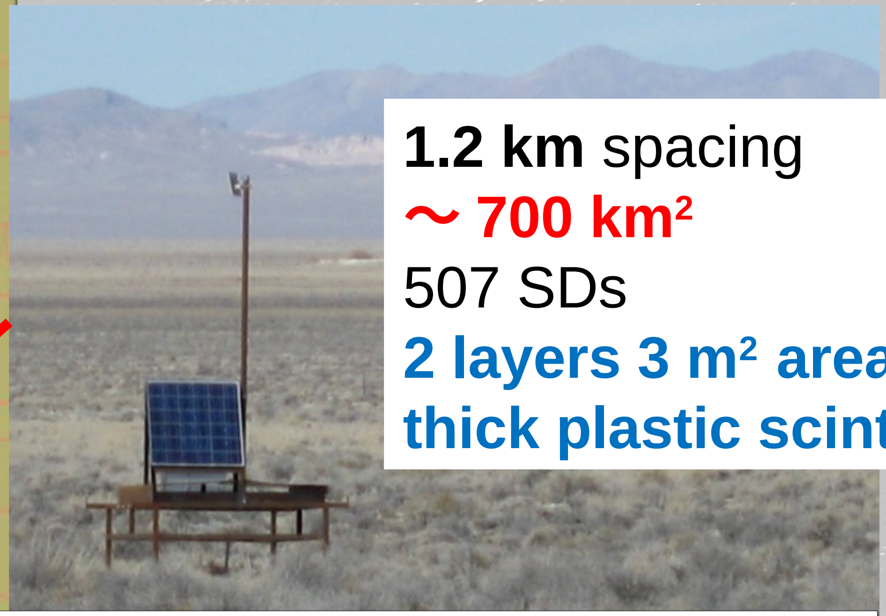


Telescope Array experiment



Latitude 39.30°N
Longitude 112.91°W
Altitude: 1382 m

Surface Detector (SD)



1.2 km spacing
~ 700 km²
507 SDs
2 layers 3 m² area 1.2 cm thick plastic scintillators

- **Largest cosmic-ray observatory in the Northern hemisphere**
- **Hybrid observation by SD and FD**
- **Efficienet for E > 10^{18} eV**
- **Fully efficient for E > 10^{19} eV**

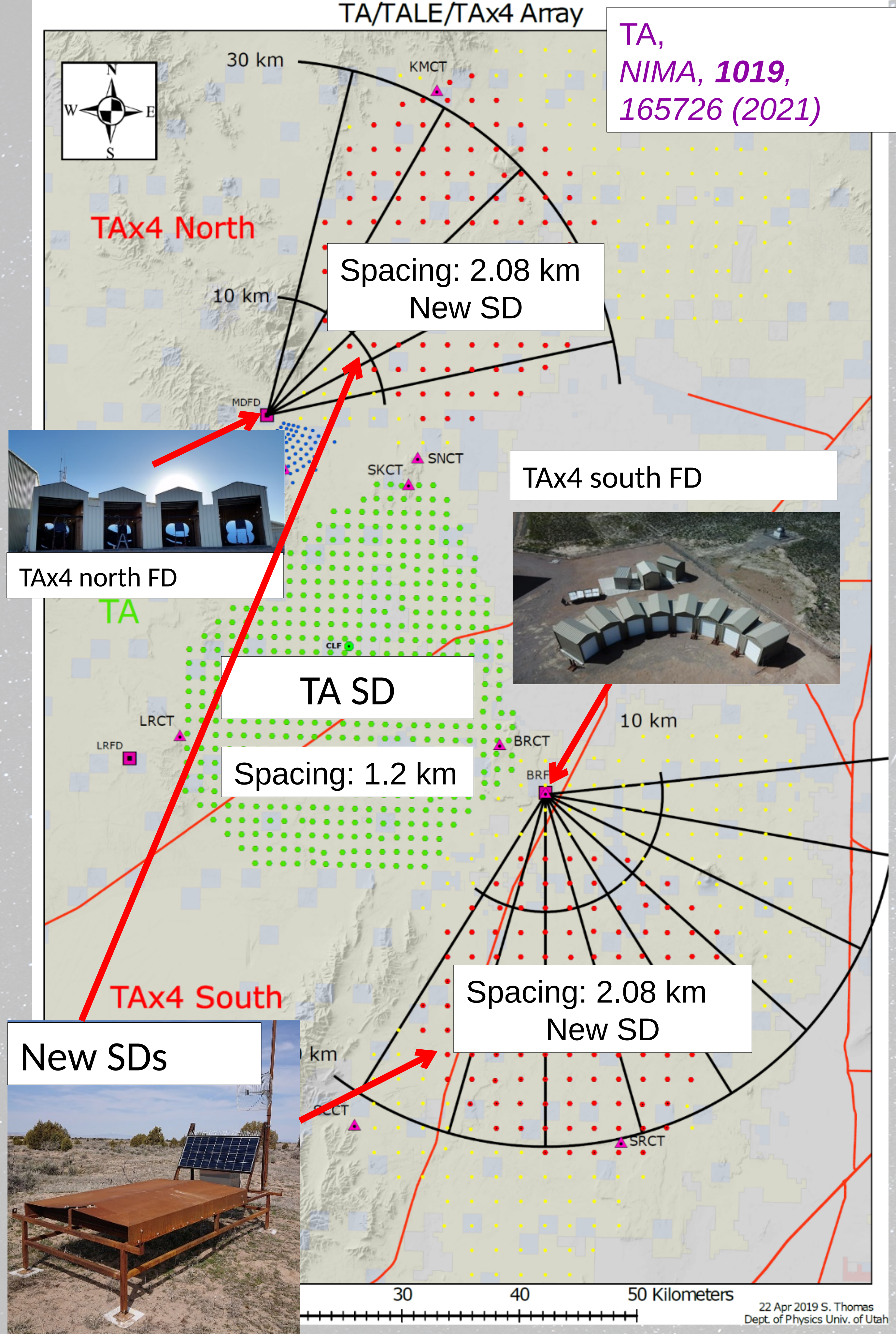
12 telescopes

Fluorescence Detector (FD) station

12 telescopes

Full operation since May **2008** @ **Utah, USA**

TAx4 extension



TA, *NIMA*, ***1019***, *165726 (2021)*

TAx4 was developed to accelerate the pace of data collection at the highest energies.

500 new SDs with **2.08 km** spacing (TASD: 1.2 km spacing)

New SDs and TA SDs plan to cover

4×TA SD detection area (~2800 km^2)

More than half of the new SDs (**257 SDs**) were deployed in 2019.

Deployed SDs are running stably since Nov. 2019.

Current detection area ~**1700 km^2**.

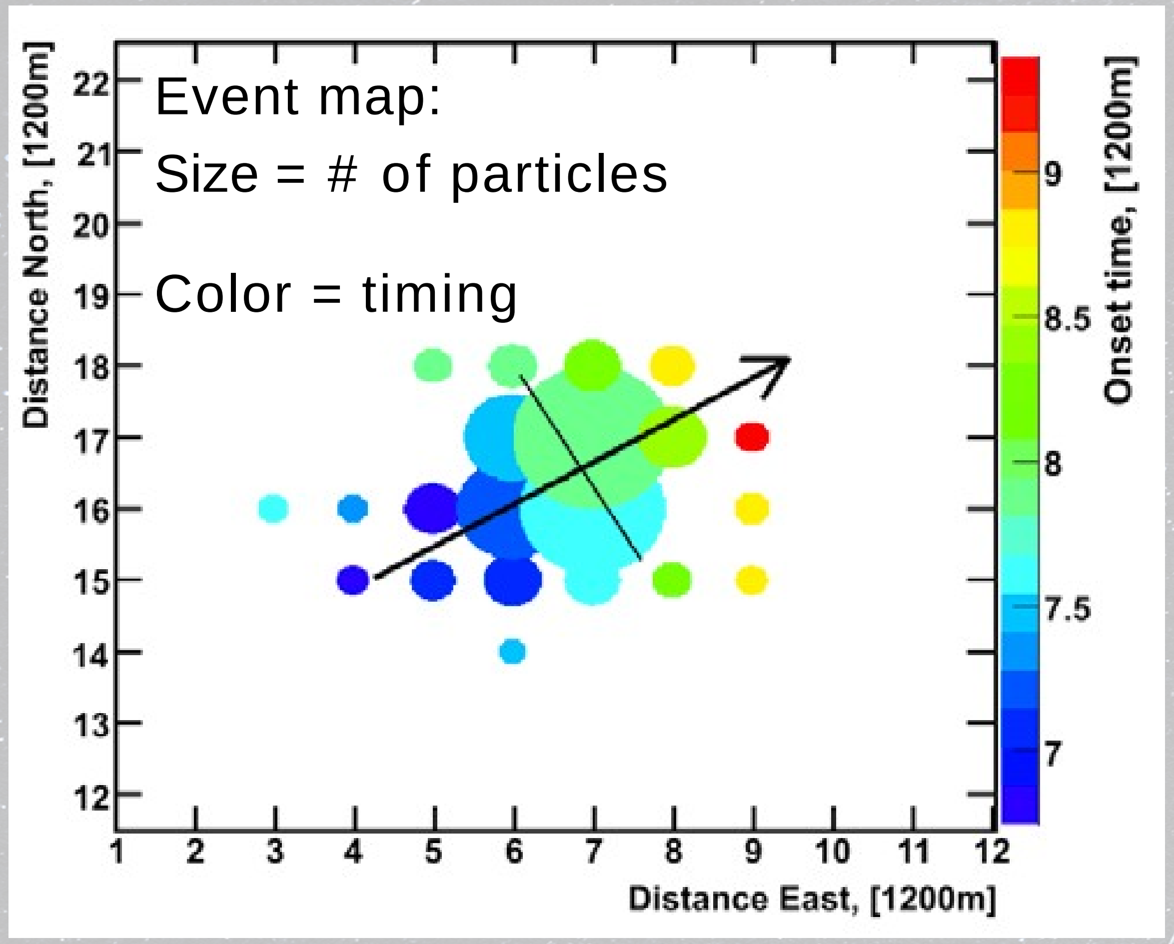
Two new Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)

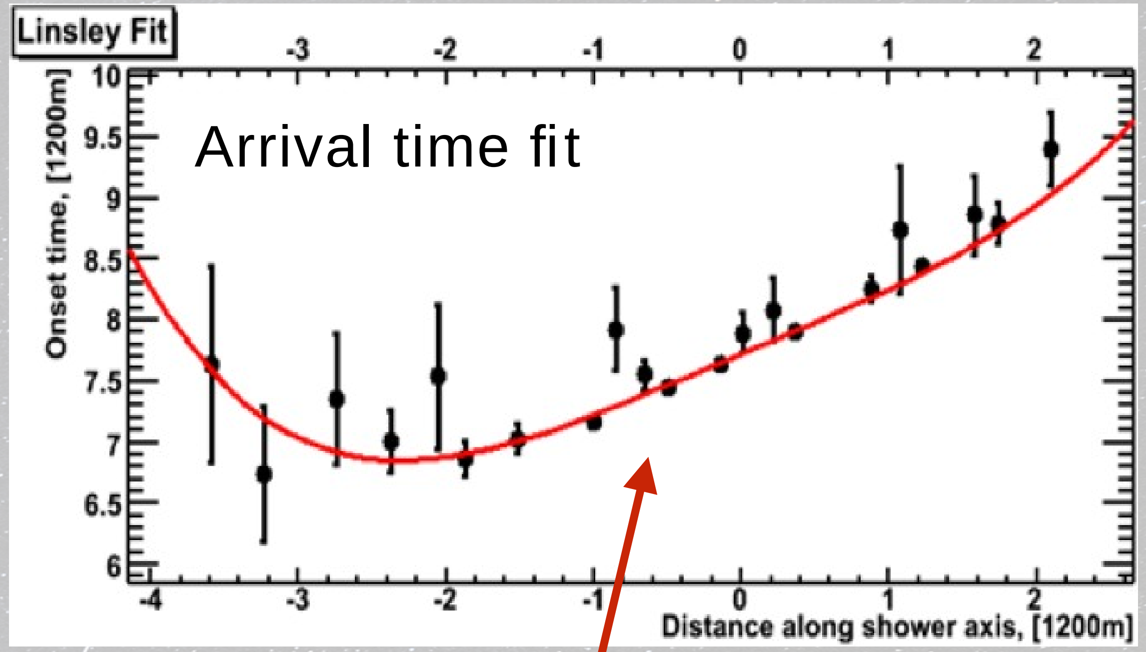
FD(north): stable run since Jun. 2018.

FD(south): stable run since Sep. 2020.

- **Extension for cosmic rays with higher energies**
- **Sparse SD array (spacing: 2.08 km)**
- **Two new FD stations**
- **Hybrid observation by SD and FD**
- **Efficient for E > 10^{19} eV**

UHECR events reconstruction with SD



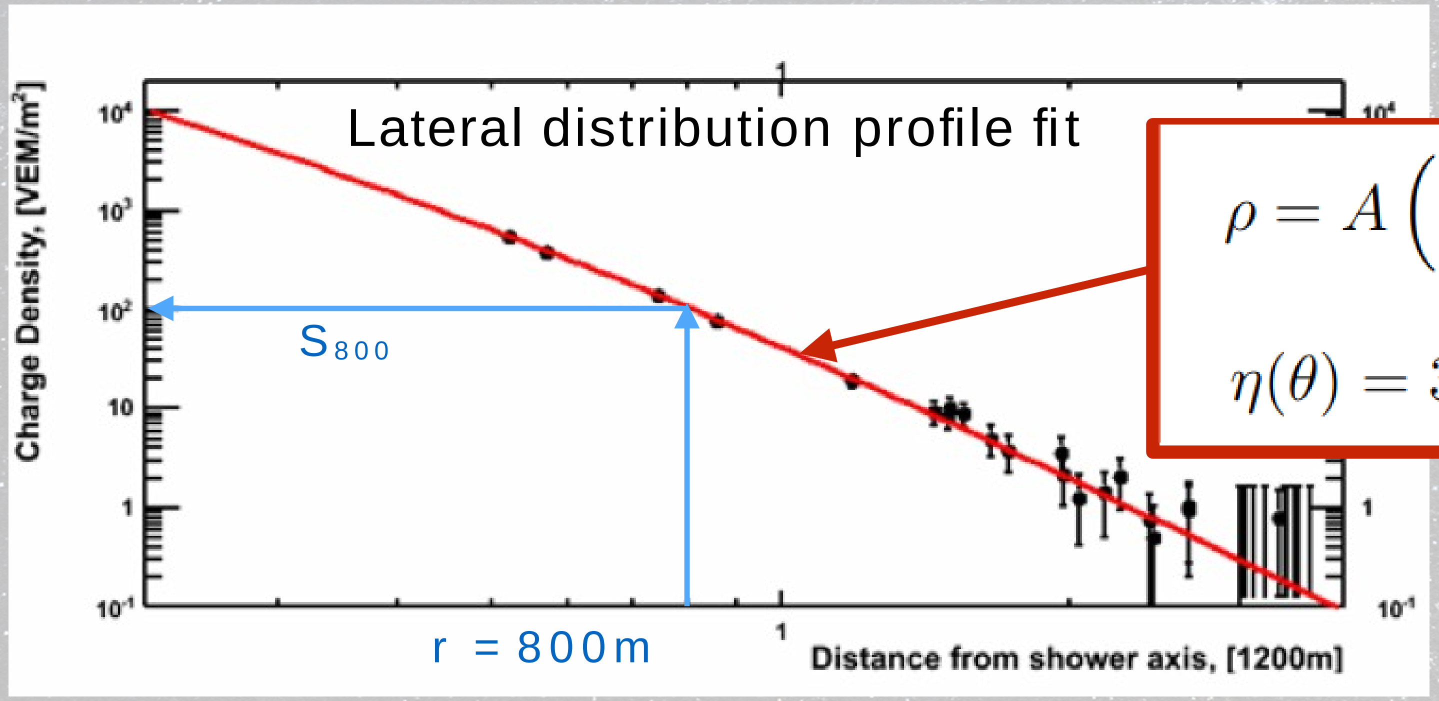


SD energies are rescaled to FD energies using FD and SD hybrid events.

$$E_{final} = E_{SD} / 1.27$$

$$\tau = a\left(1 - \frac{l}{12\times10^3\mathrm{m}}\right)^{1.05}\left(1.0 + \frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Timing fit (modified Linsley) --> shower geometry



$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1 + \frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1 + \left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

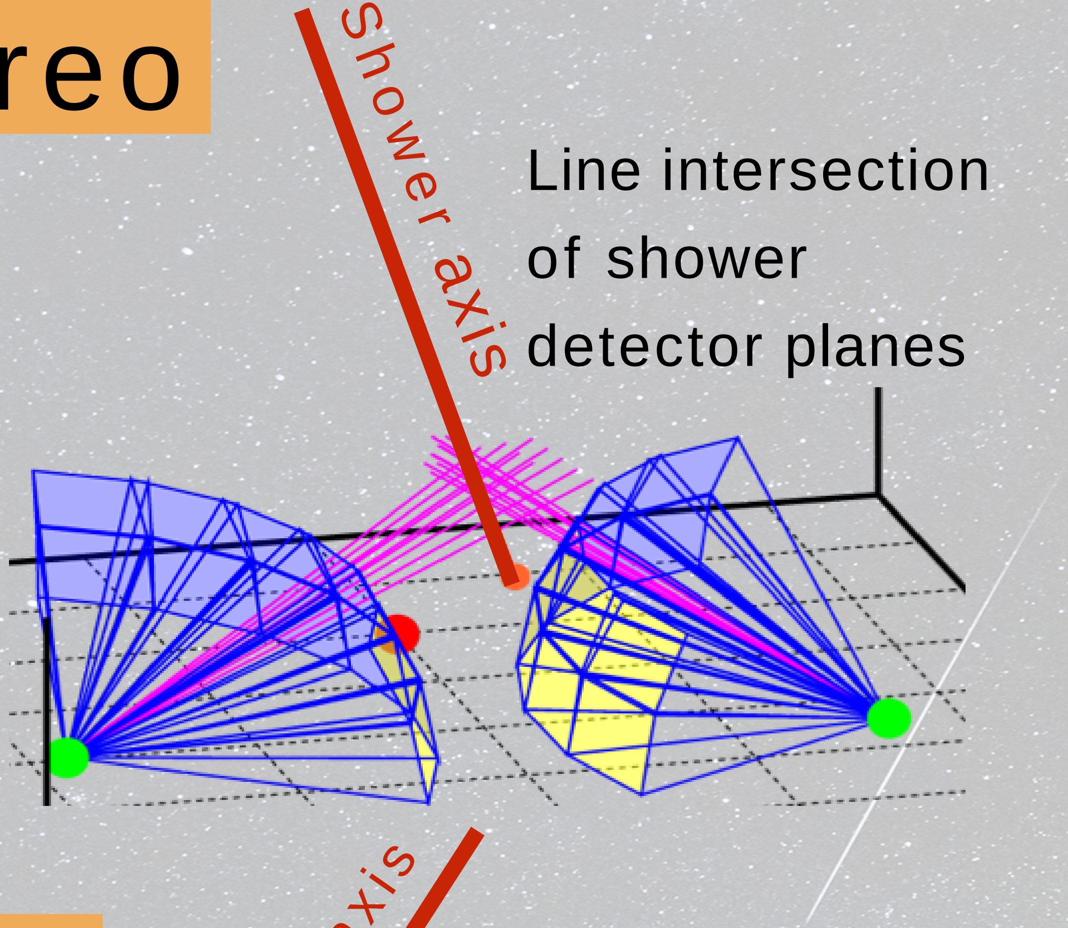
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta) - 1\right]$$

S_{800} --> primary energy

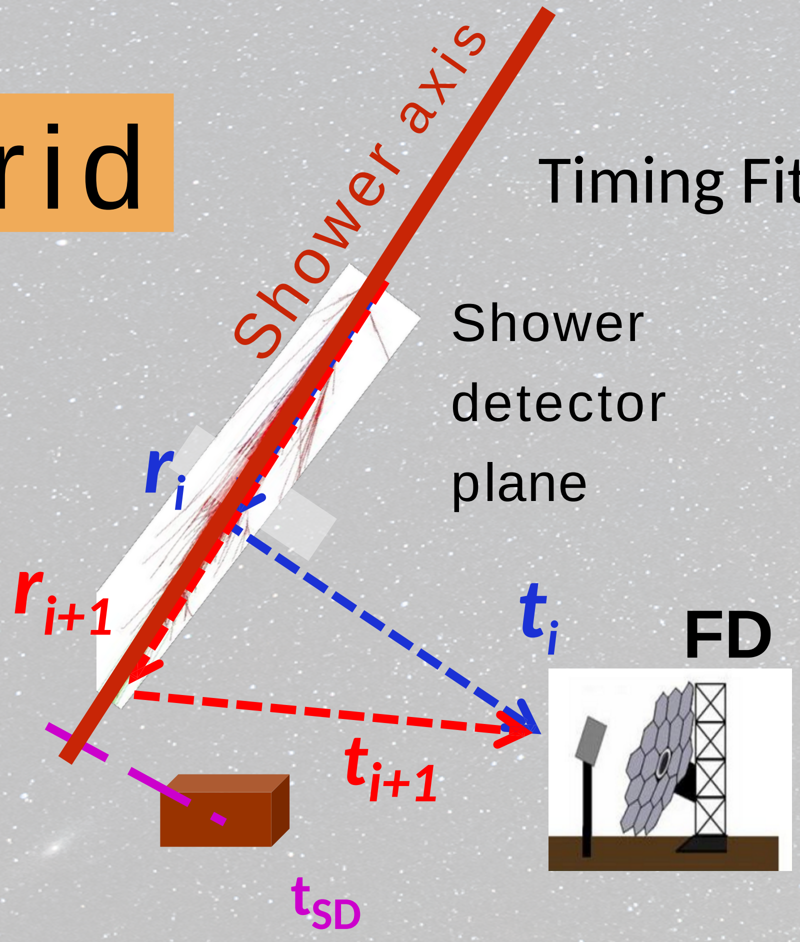
TAx4 SD (2.08 km spacing):
combined fit of timing and lateral distribution

UHECR events reconstruction with FD

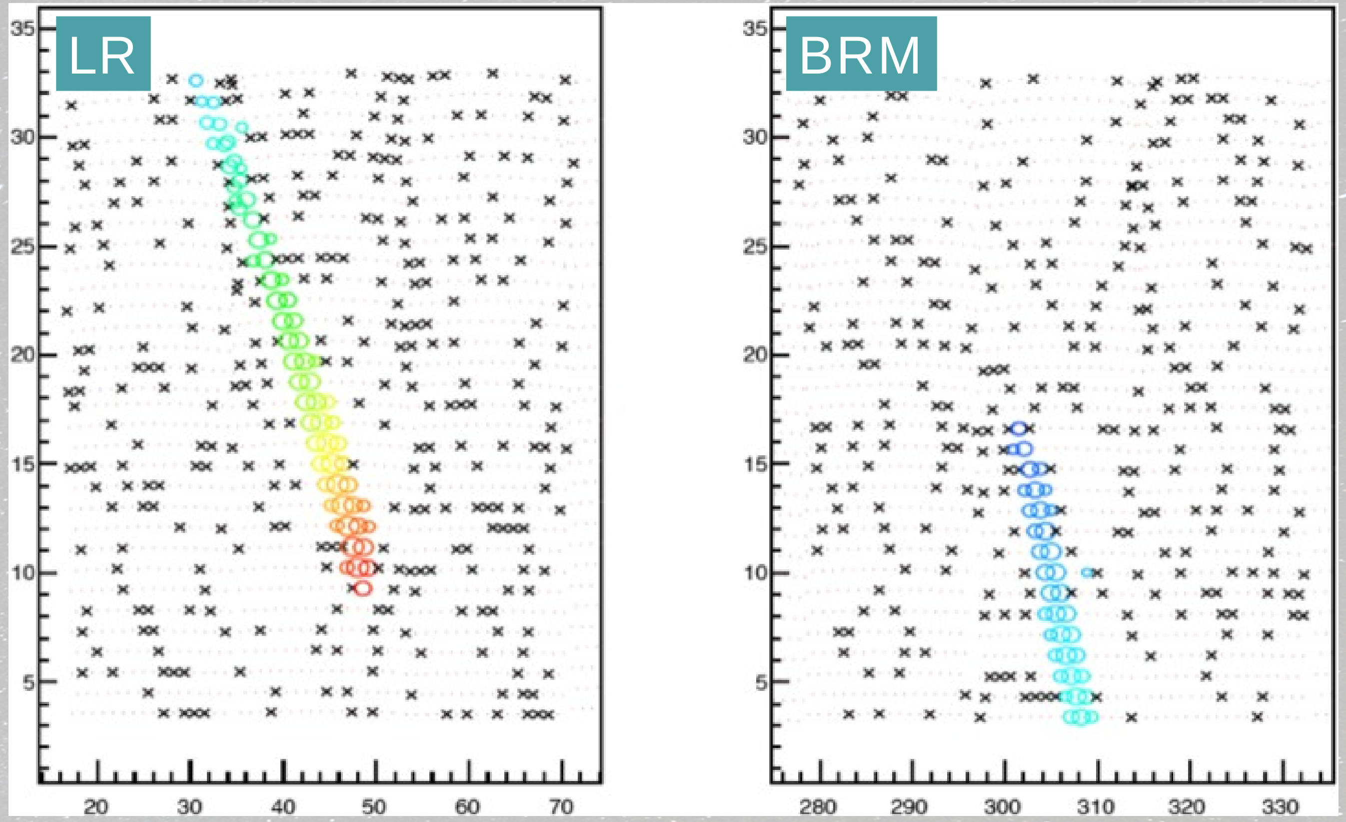
Stereo



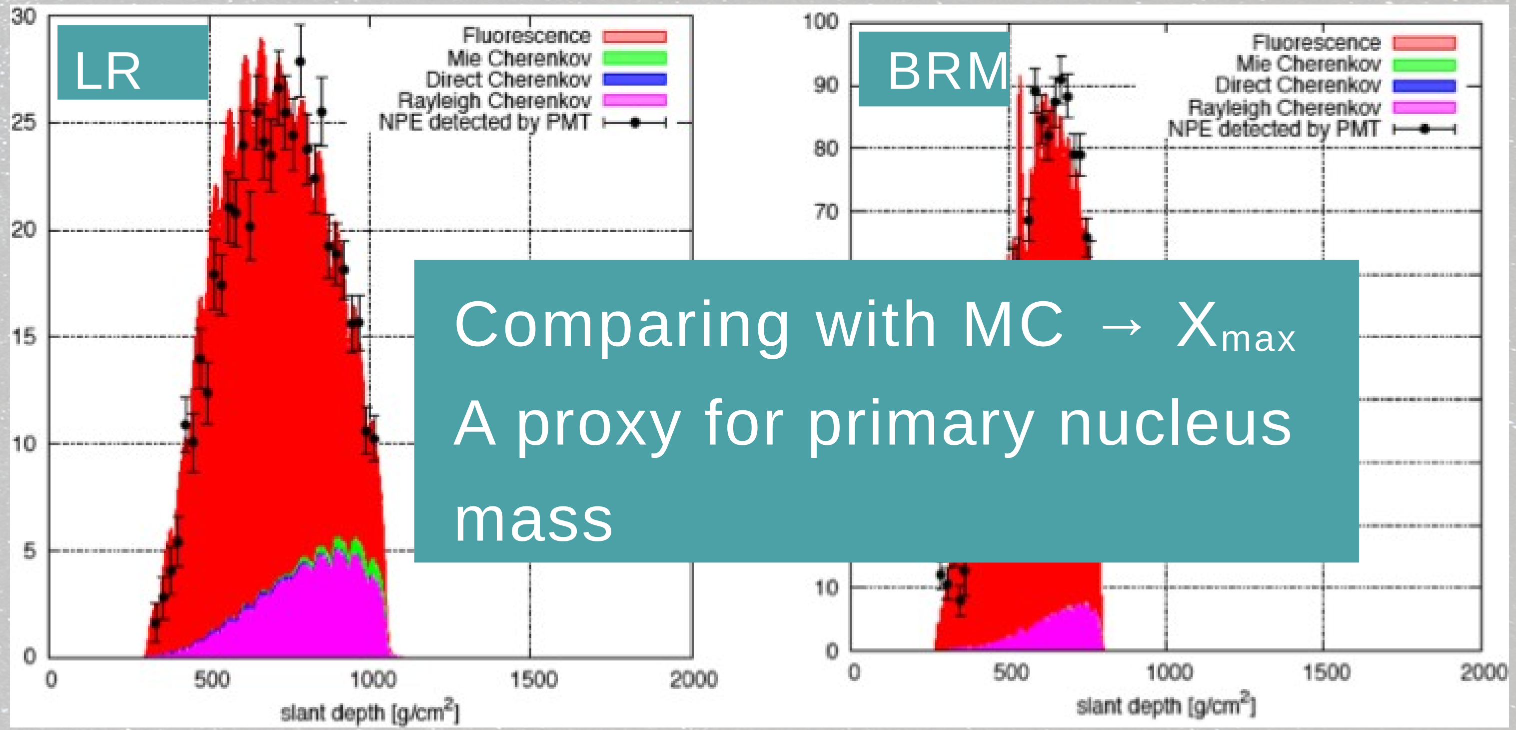
Hybrid



Observed images



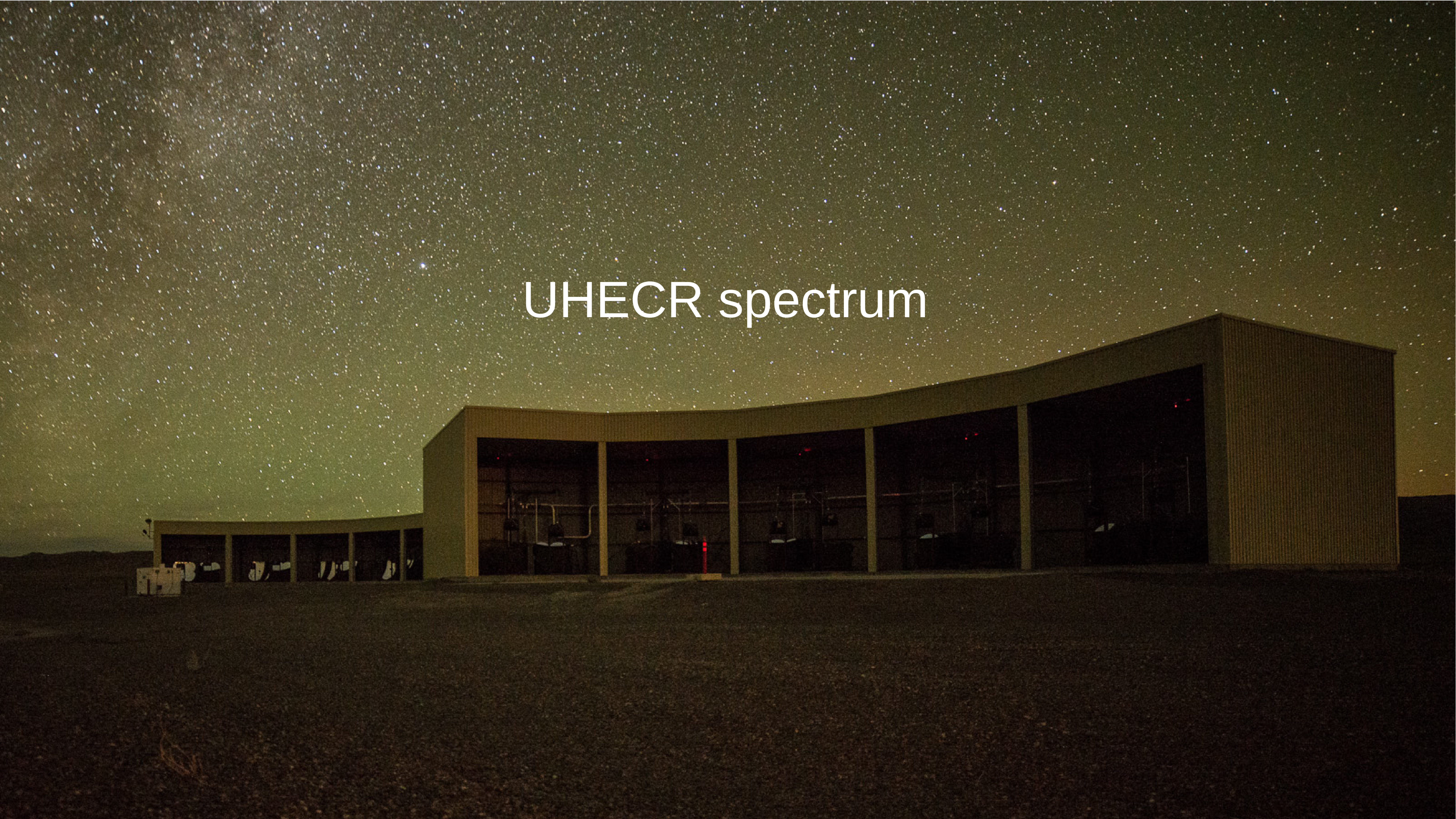
Reconstructed shower profiles



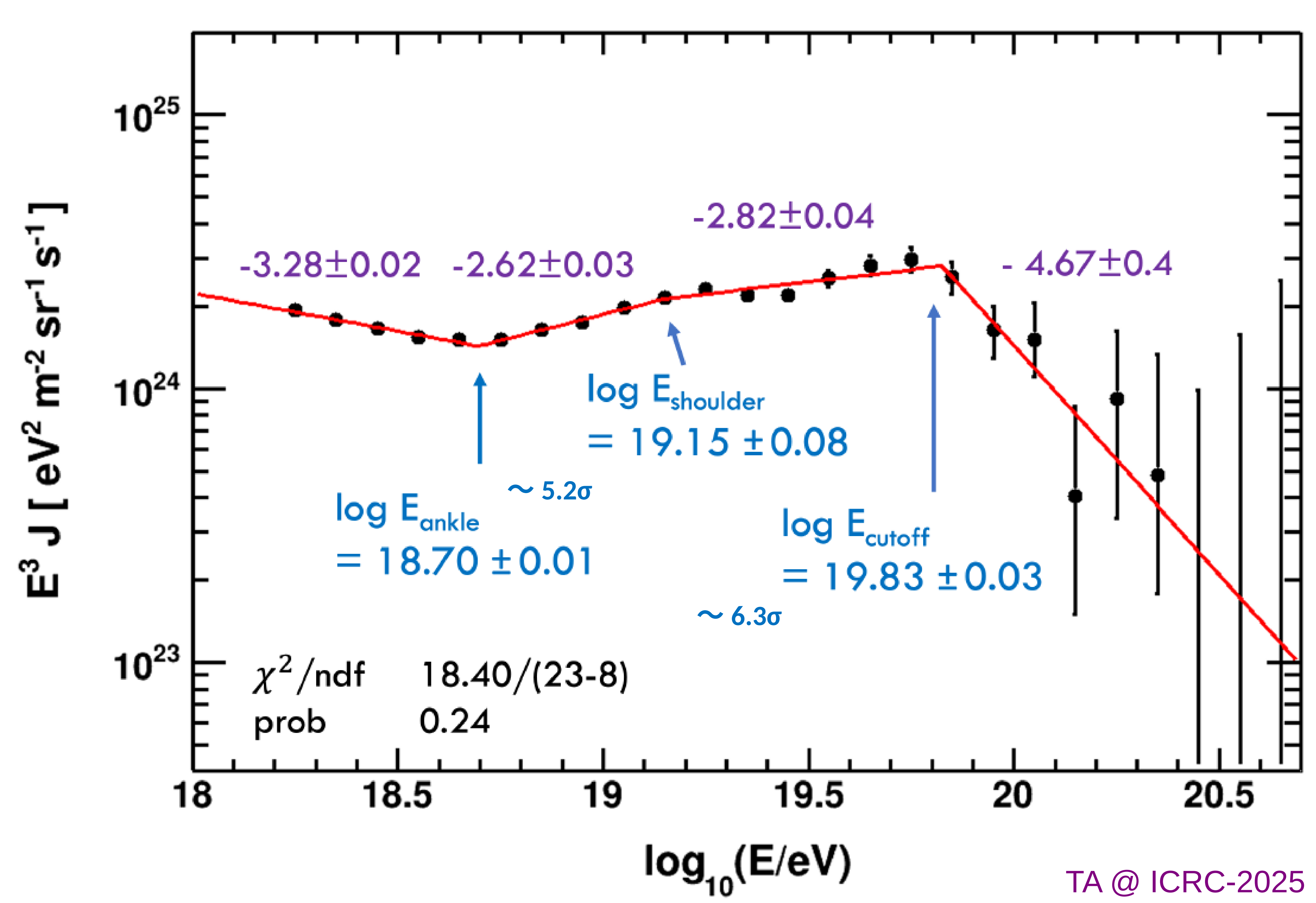
Comparing with MC → X_{max}

A proxy for primary nucleus mass

UHECR spectrum

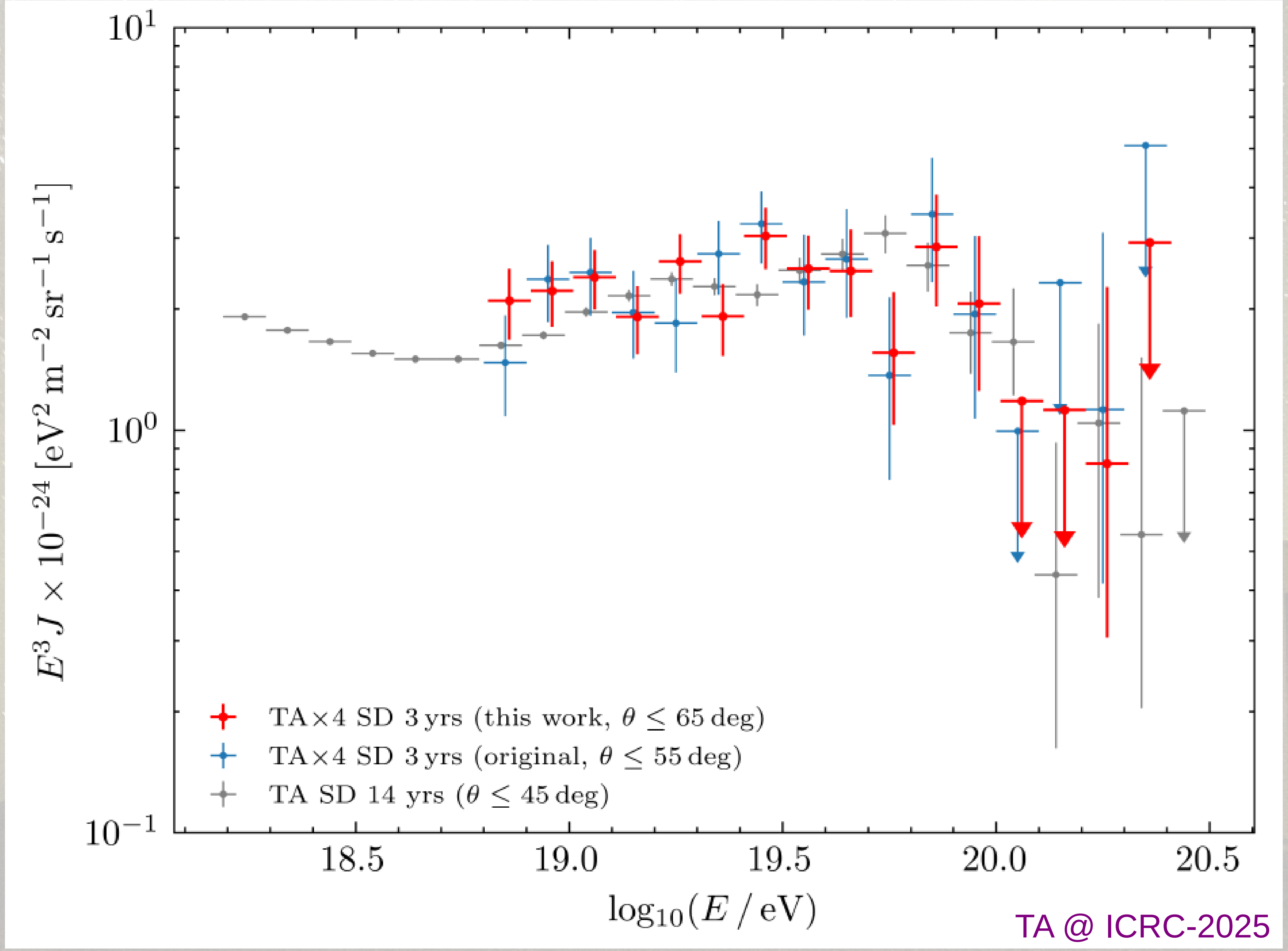


Energy spectrum in full-sky with TA SD



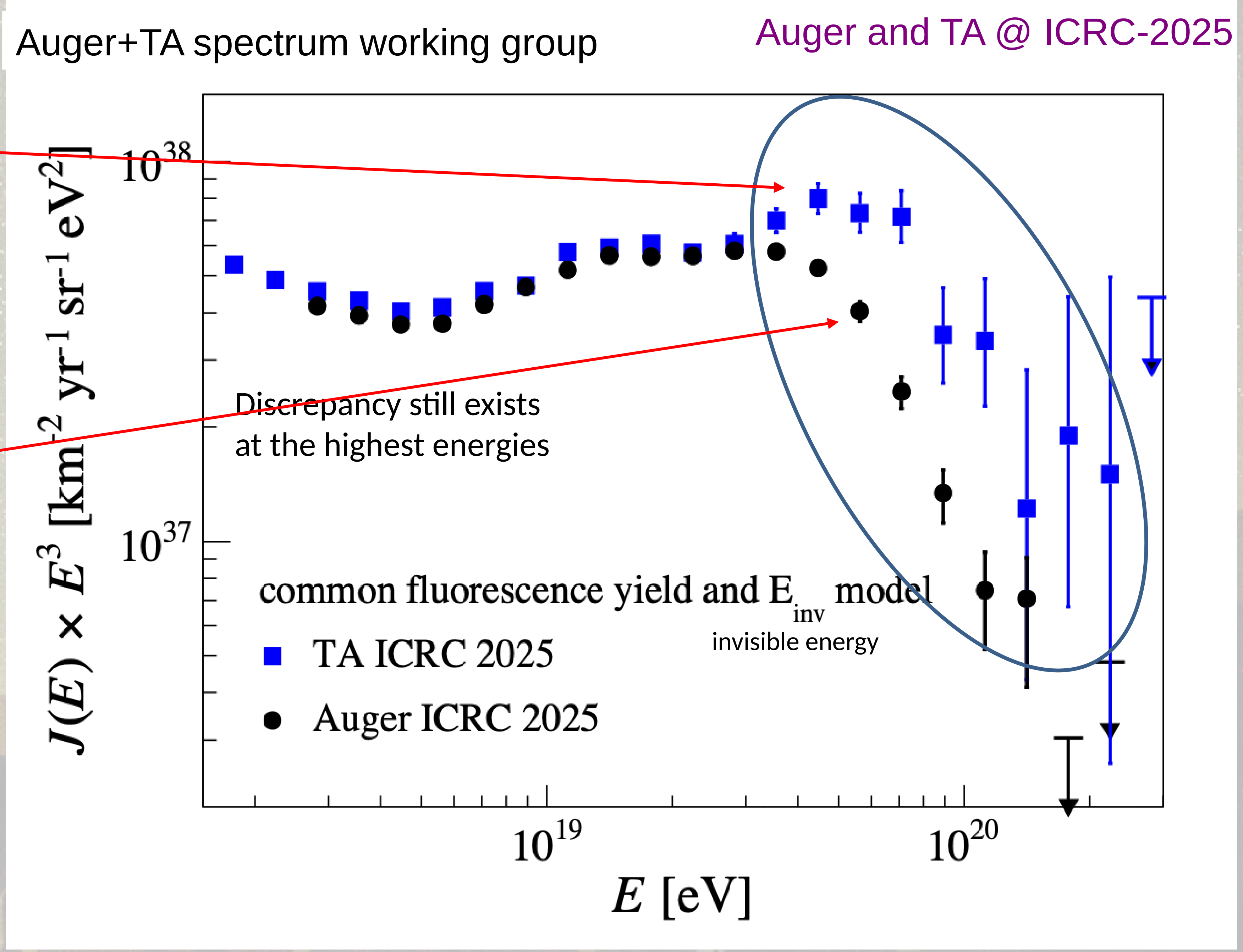
- 16 years TA SD data
  - 2008-05-11 – 2024-05-10
- Three breaks are detected above 1 EeV.
- Position of new «shoulder» feature (14 EeV) is consistent with Auger «instep», spectral indices are not consistent

Energy spectrum in full-sky with TAx4 SD



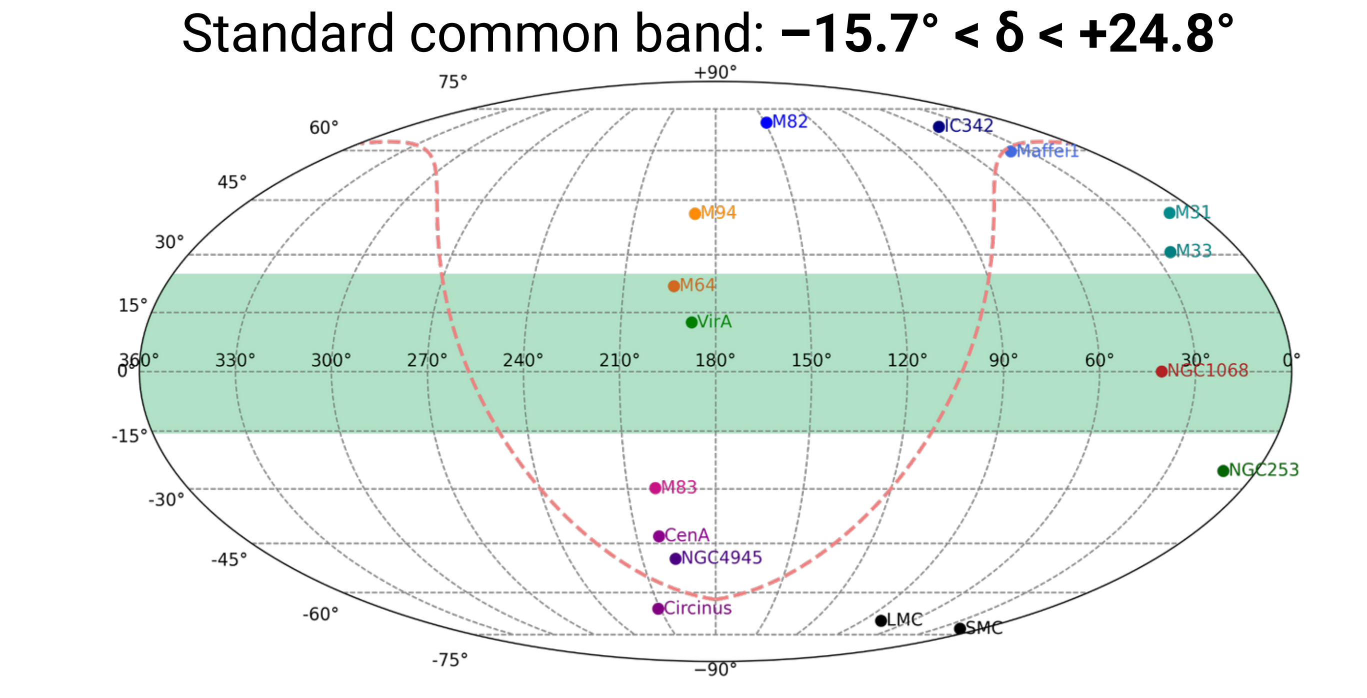
- 3 years TAx4 SD data
  – Oct. 2019 – Sep. 2022
- Reasonable agreement of the geometry between data and MC simulations.
- Event reconstructions with inclined shower (55-65 deg.) are newly included.
- Consistent with TA SD energy spectrum.

Comparison of TA and Auger spectra



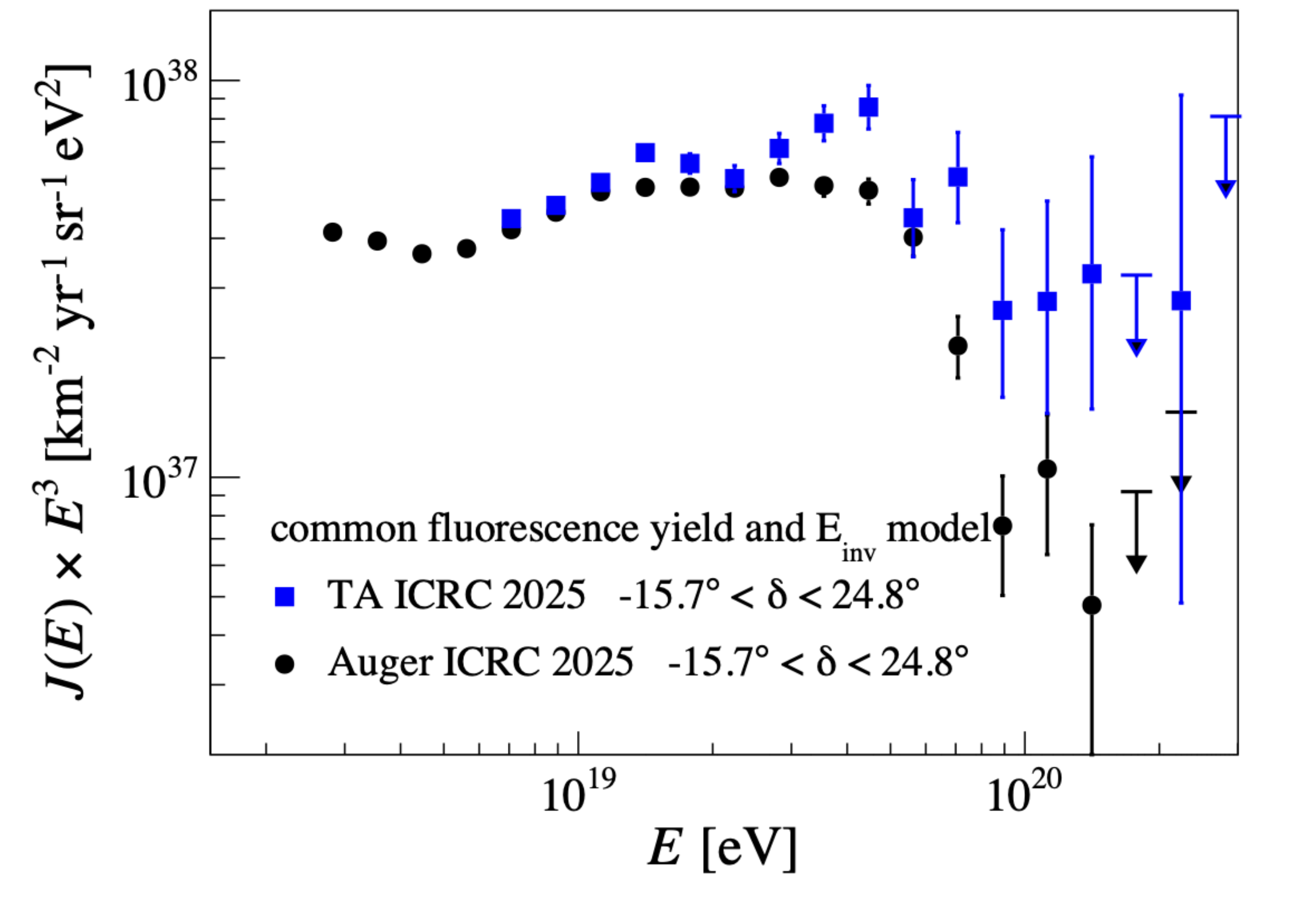
- Full spectrum shape is the same: ankle + suppression at the highest energies
- Flux values at supression region are different; even when using the same EAS models for analysis

Spectra comparison in the common declination band

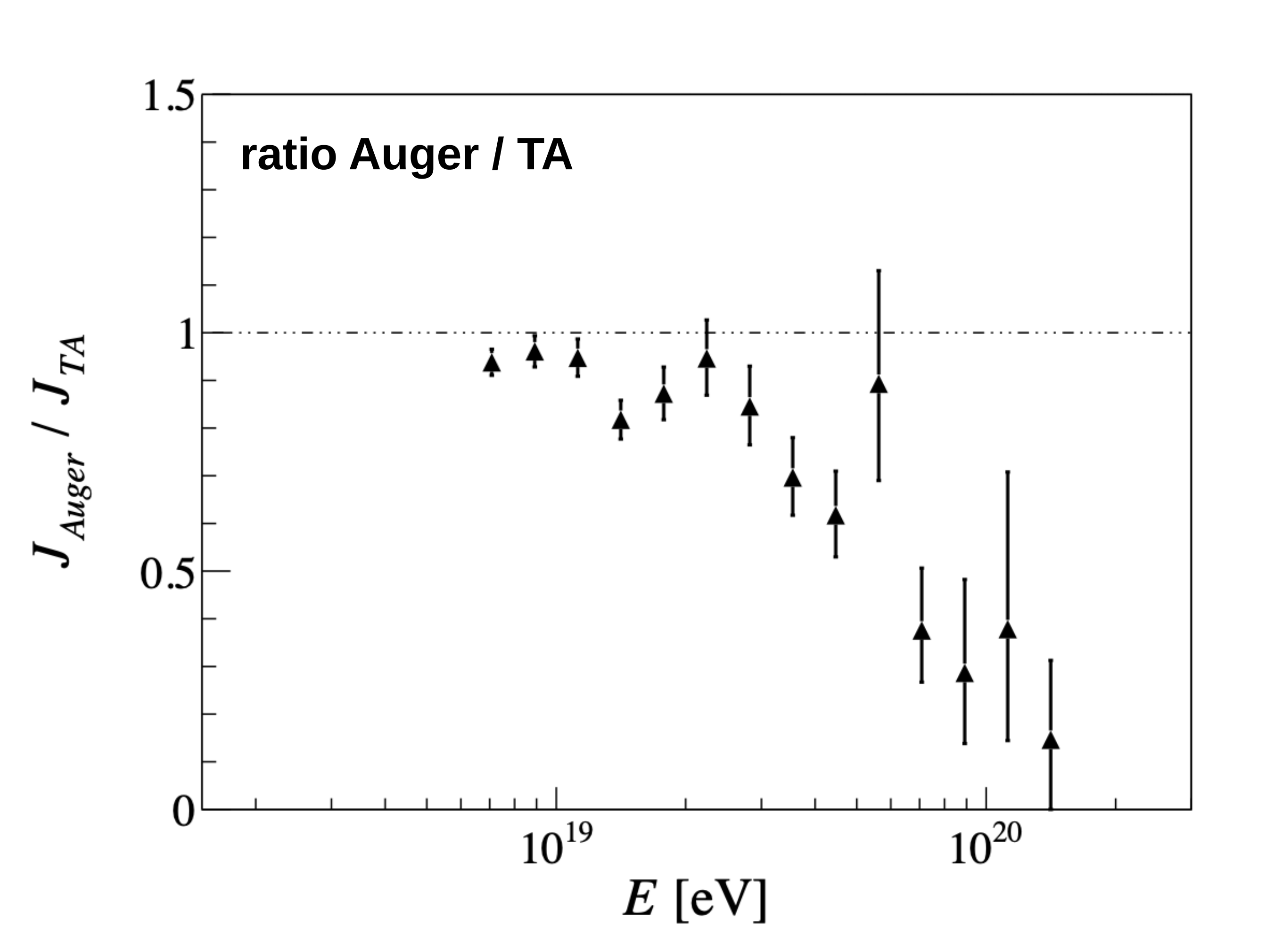


- **same declination range** reduce impact of potential sky-dependent astrophysical effects
- energy range above full efficiency for both the experiments
- remaining significant difference at the highest energies
- same results once accounted for the different directional exposures

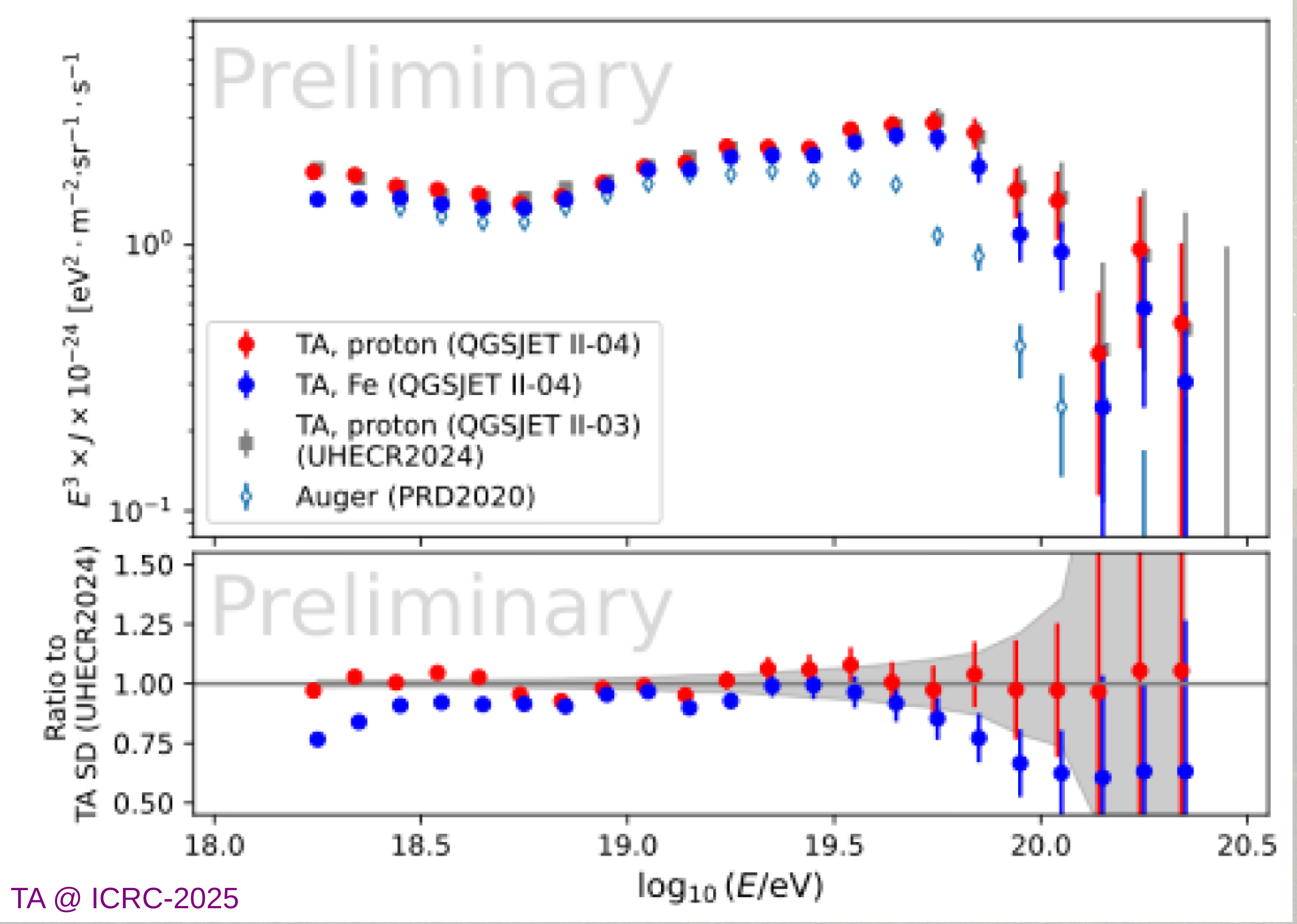
Auger and TA @ ICRC-2025



Problem still not solved

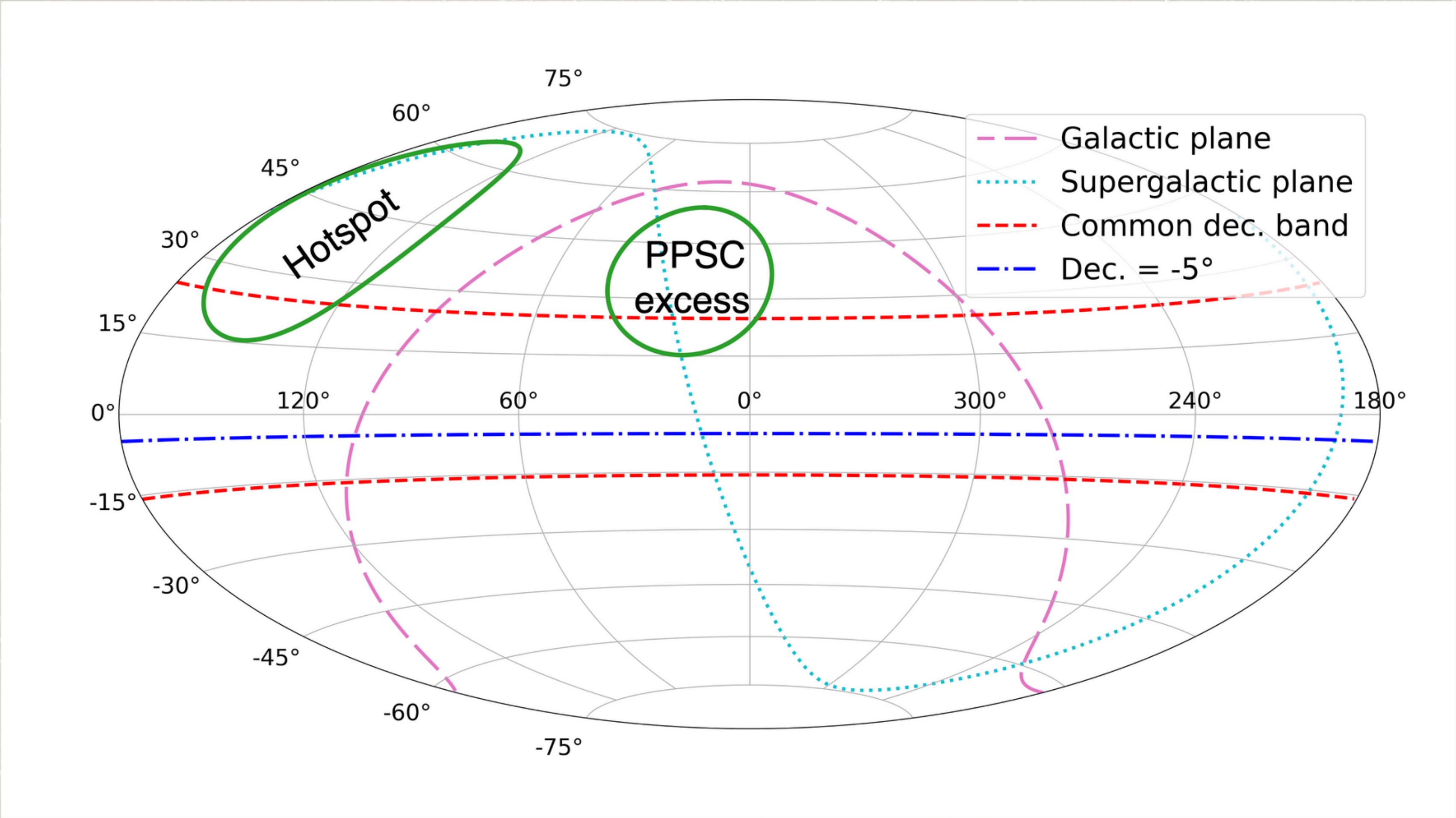


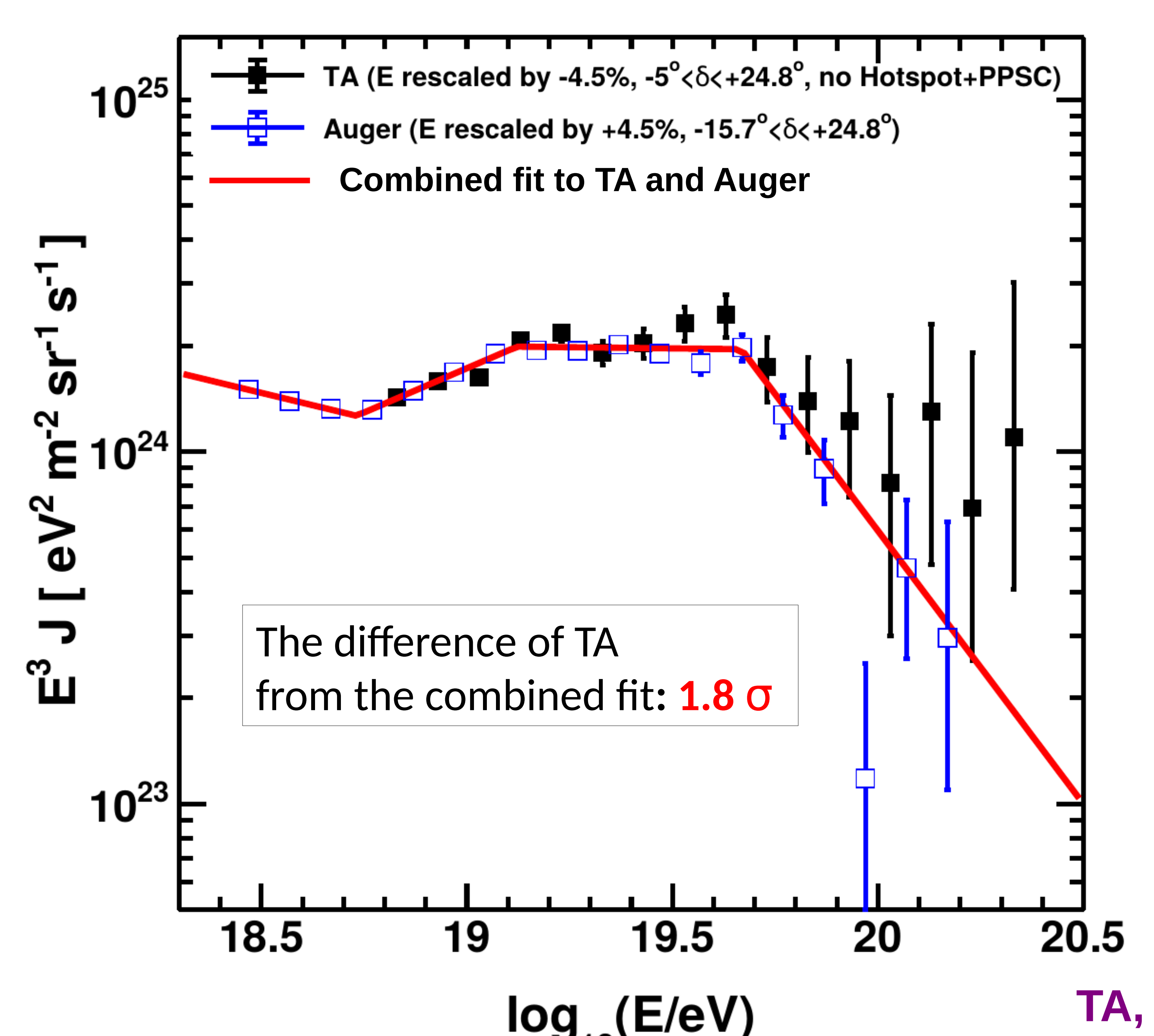
What if we assume pure iron for TA spectrum as an extreme case?



- Energy-independent bias is calibrated with FD-SD hybrid events.
- Energy-dependent bias was studied with extreme case of pure-iron MC simulations at entire energies.
- **The discrepancy of TA and Auger energy spectra was not explained this way**

Energy spectrum in TA for -5°< δ < 24.8° without excess regions

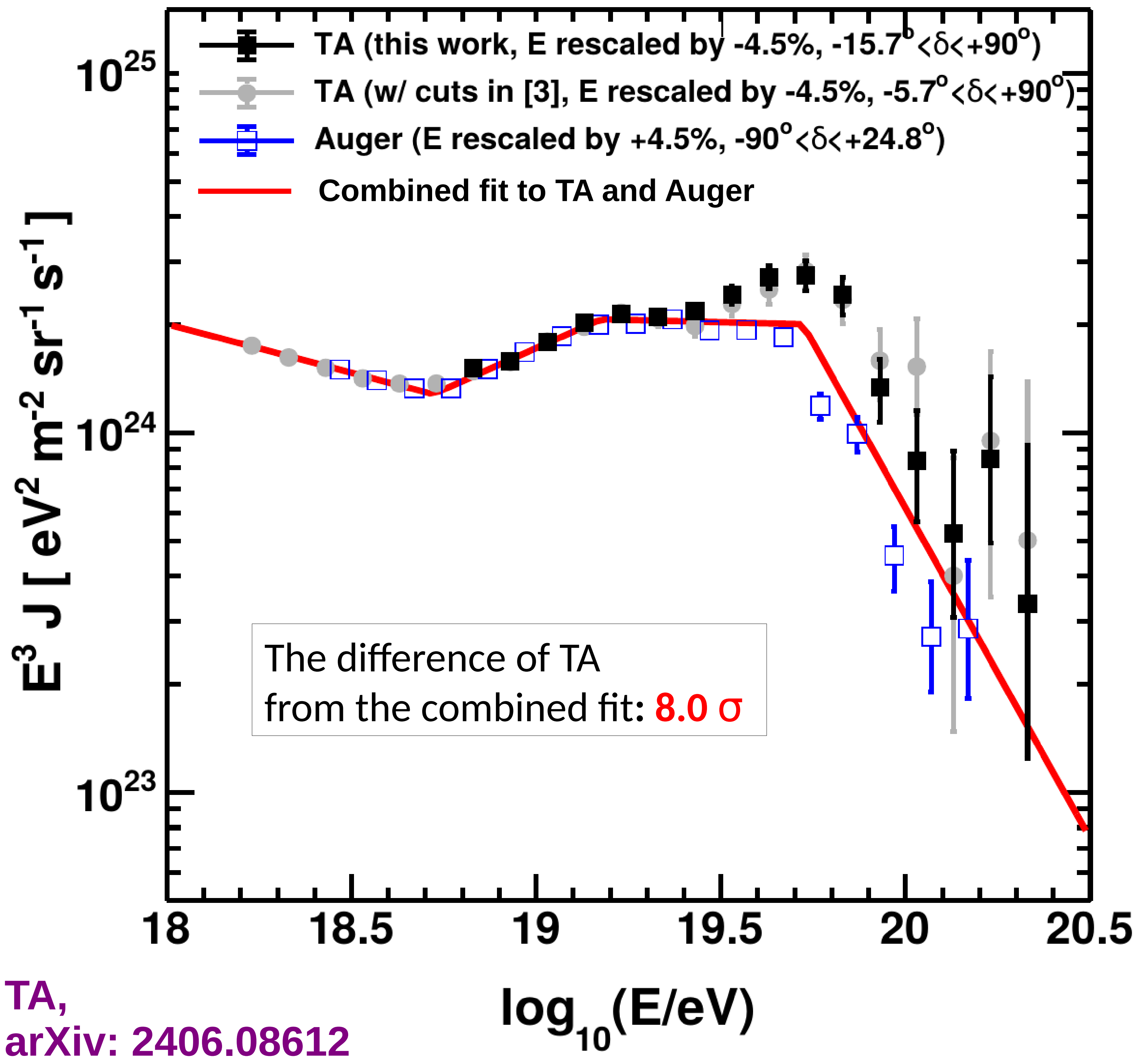




TA, arXiv: 2406.08612

Possible solution for spectra discrepancy in common band?

Energy spectrum for TA in its full field of view

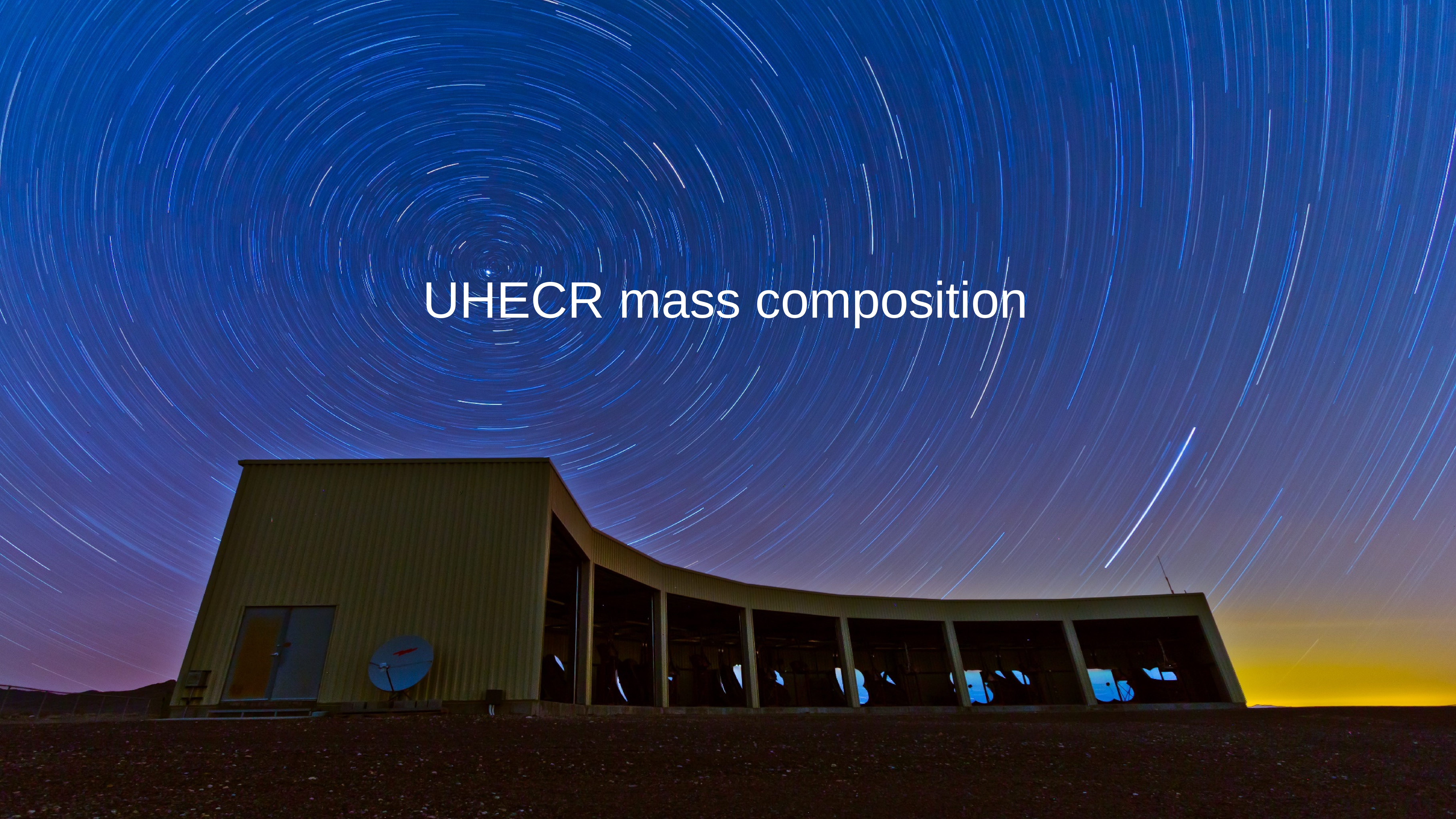


TA,
arXiv: 2406.08612

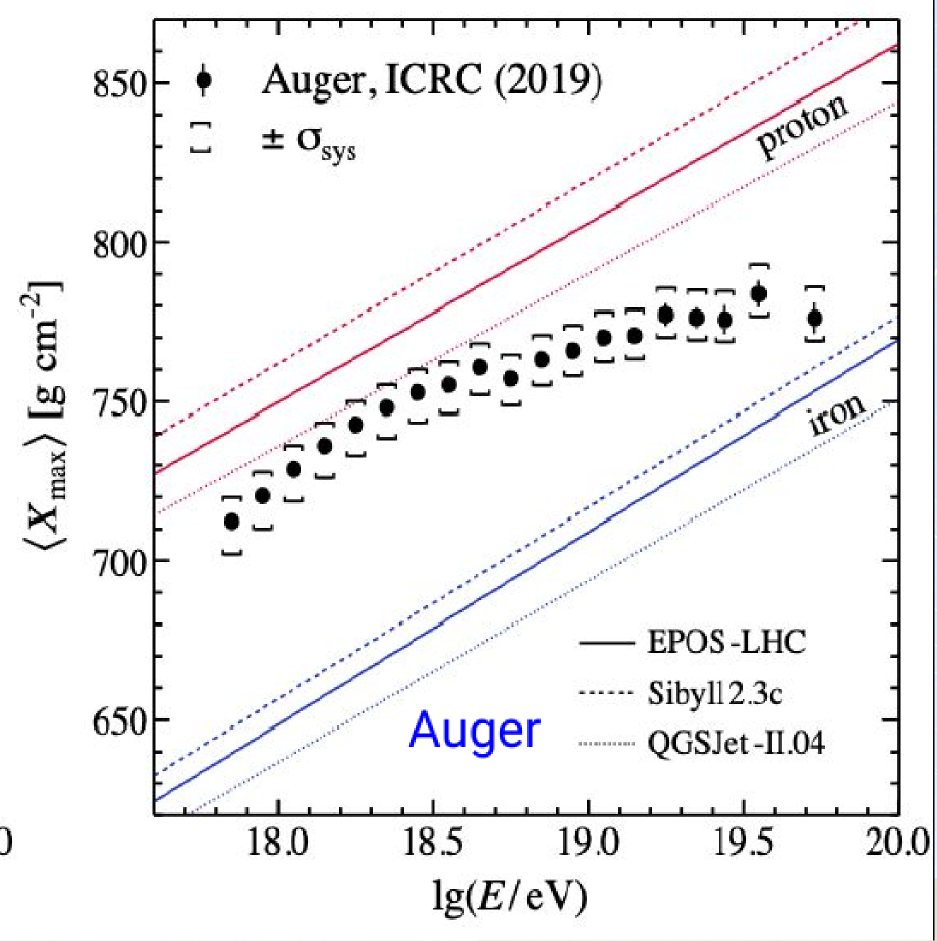
Evidence for different origin of UHECR in the Northern sky?

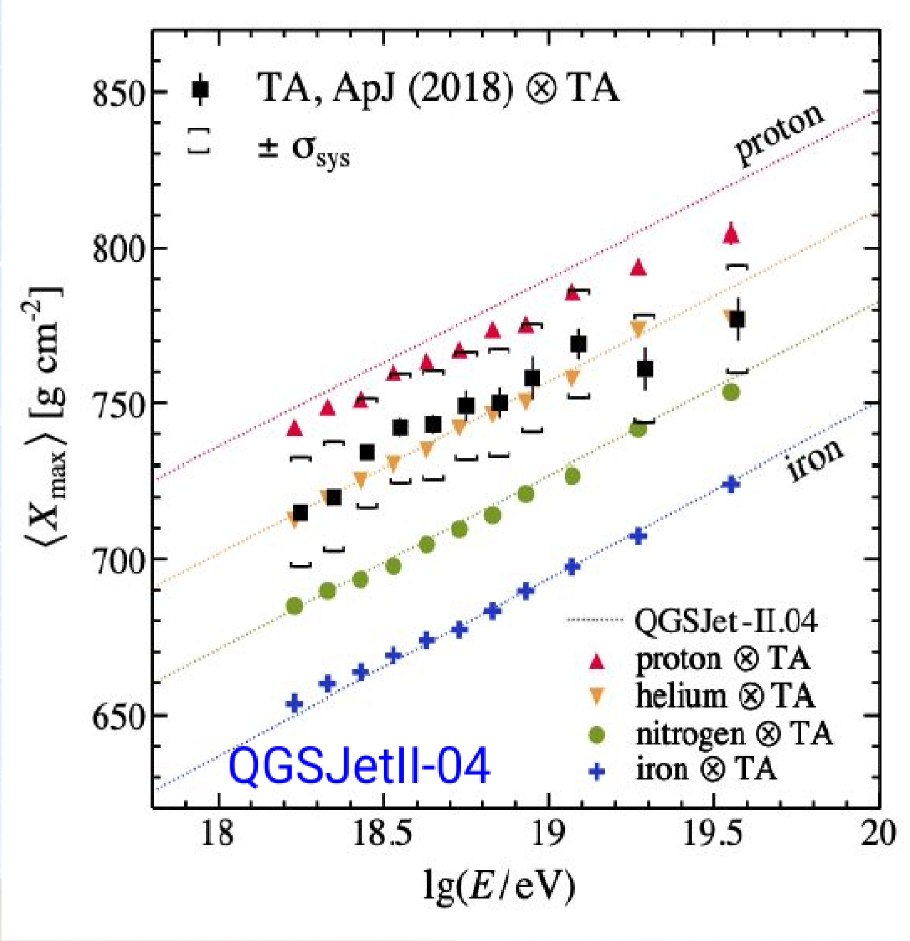
Full-sky spectrum study with one (cosmic?) experiment is needed!

UHECR mass composition



UHECR mass composition

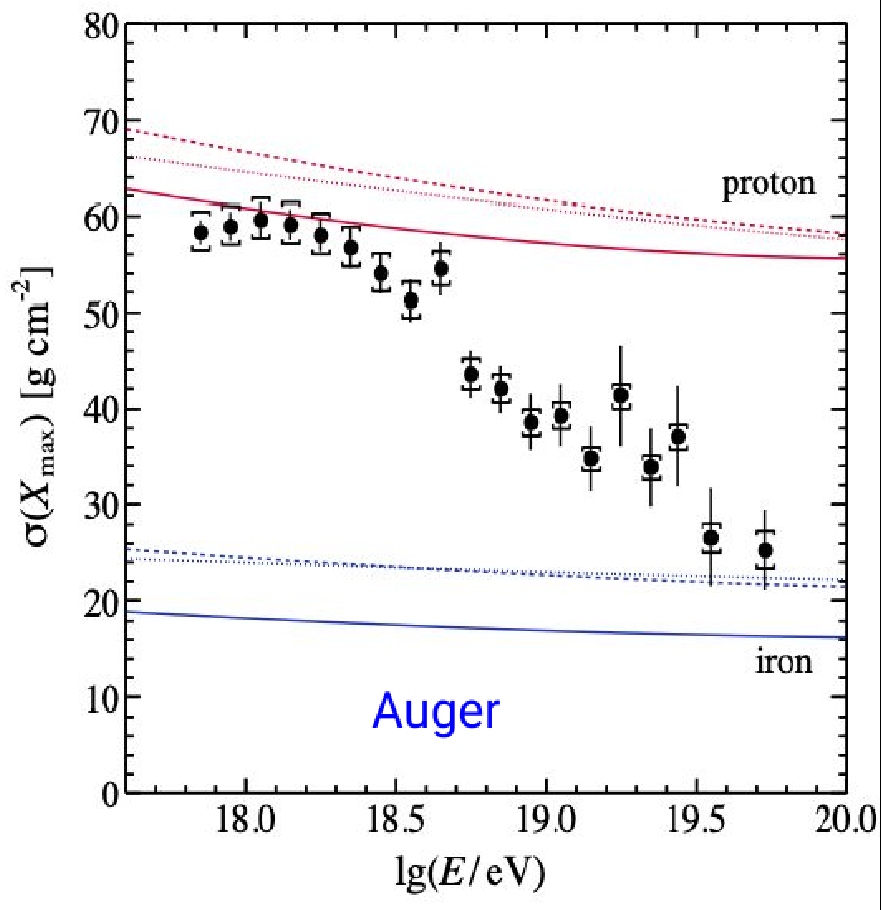


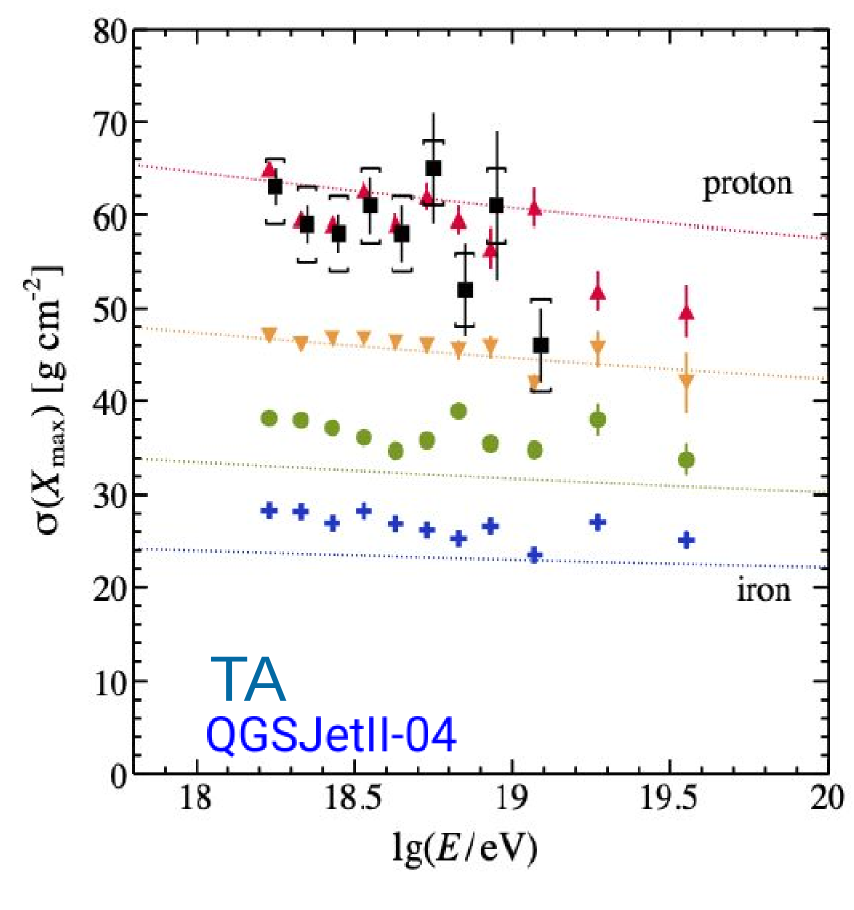


- Atmospheric depth of EAS maximum (X_{max}) is a proxy for UHECR patricle type (mass composition)
- Convenient to measure with FD
- Large shower-to-shower fluctuations: $<X_{max}>$ and $\sigma(X_{max})$ are used

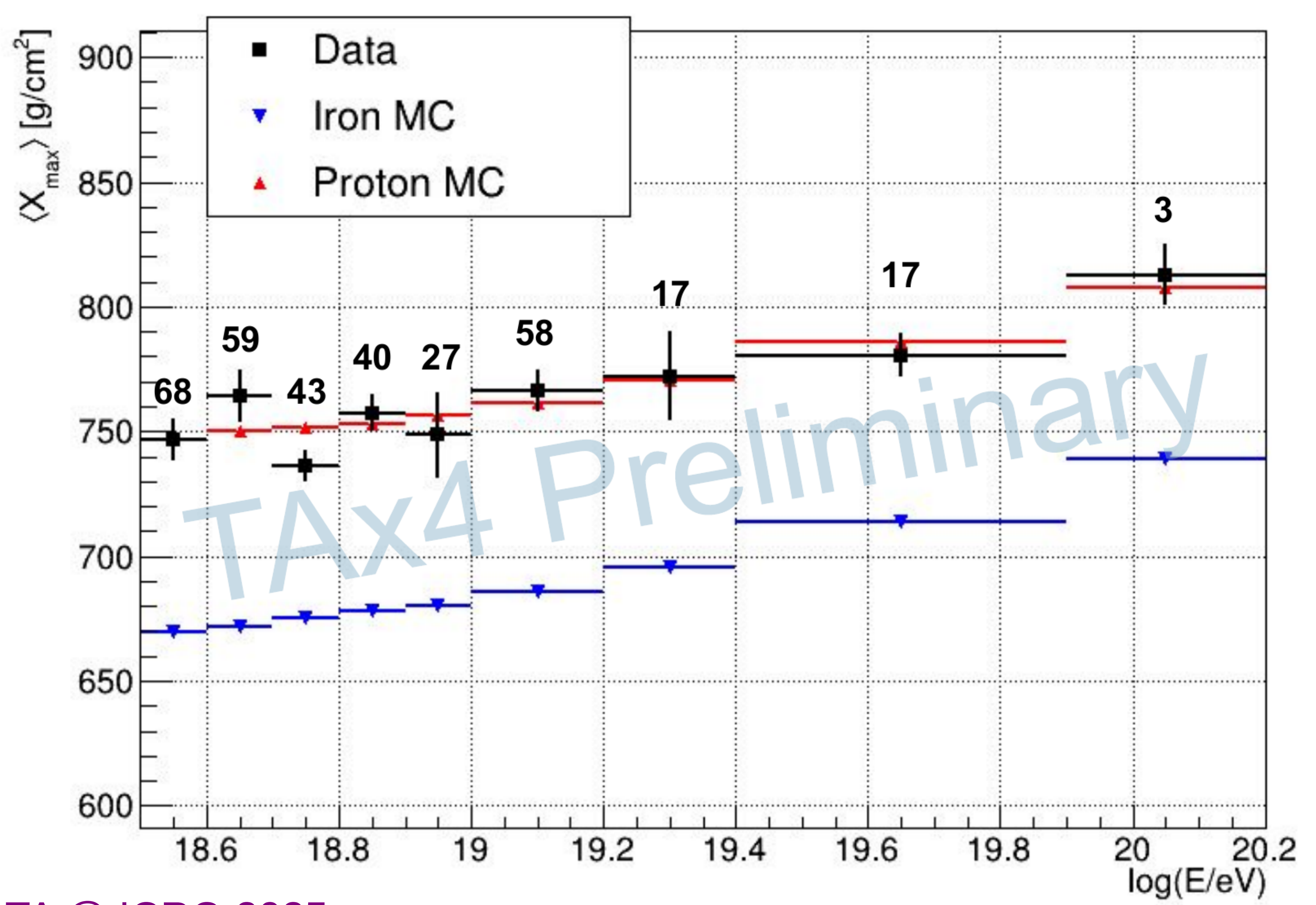
But

- FD has small statistics (~10% of total)
- Large systematic uncertainty at conversion X_{max} to particle type due to hadronic interaction models
- As a results: no consistency between TA and Auger

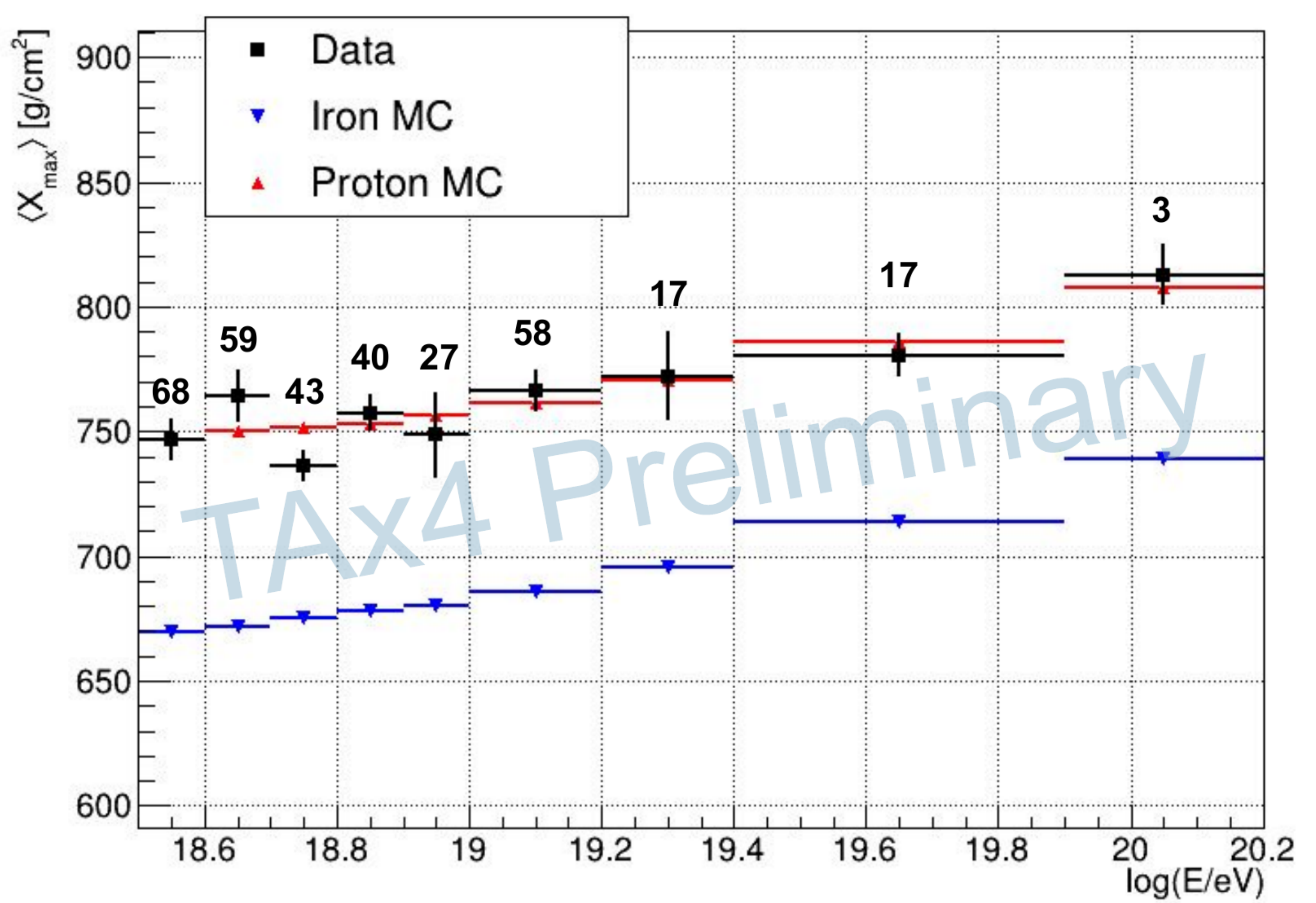




UHECR mass composition with TAx4 FD



TA @ ICRC-2025

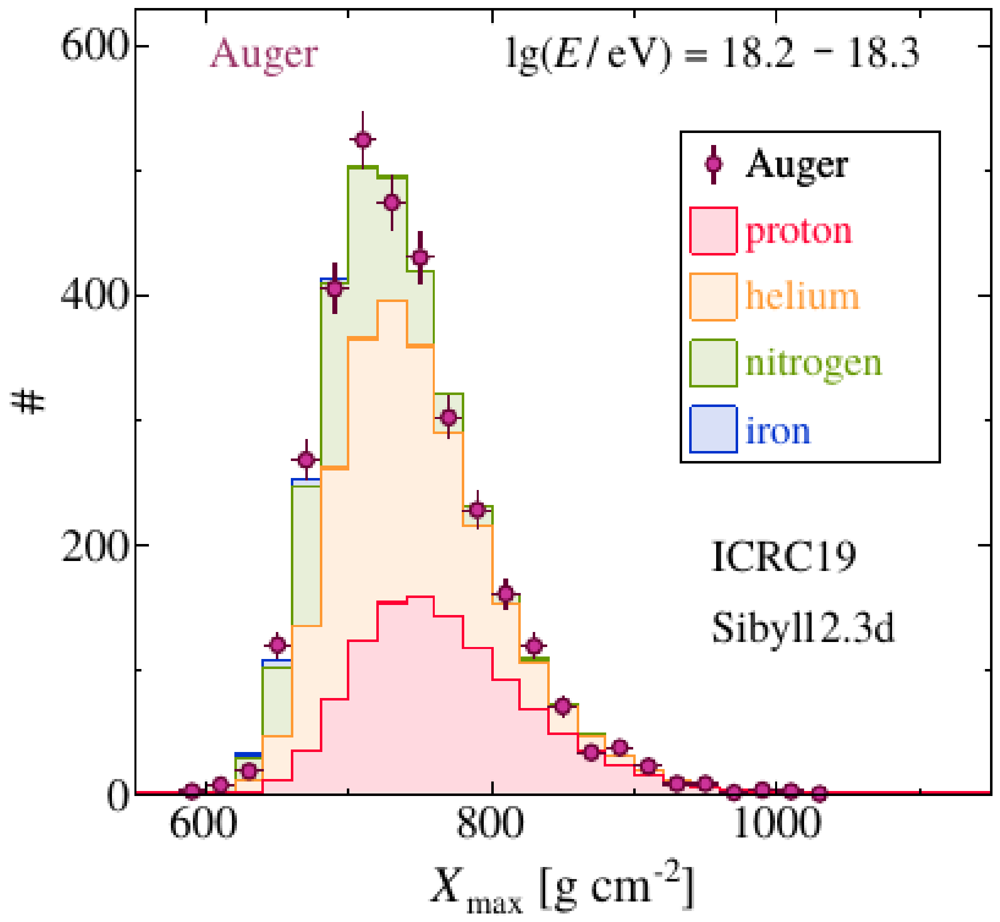


- QGSJetII-03 hadronic model is used
- Results are consistent with protons and with TA FD

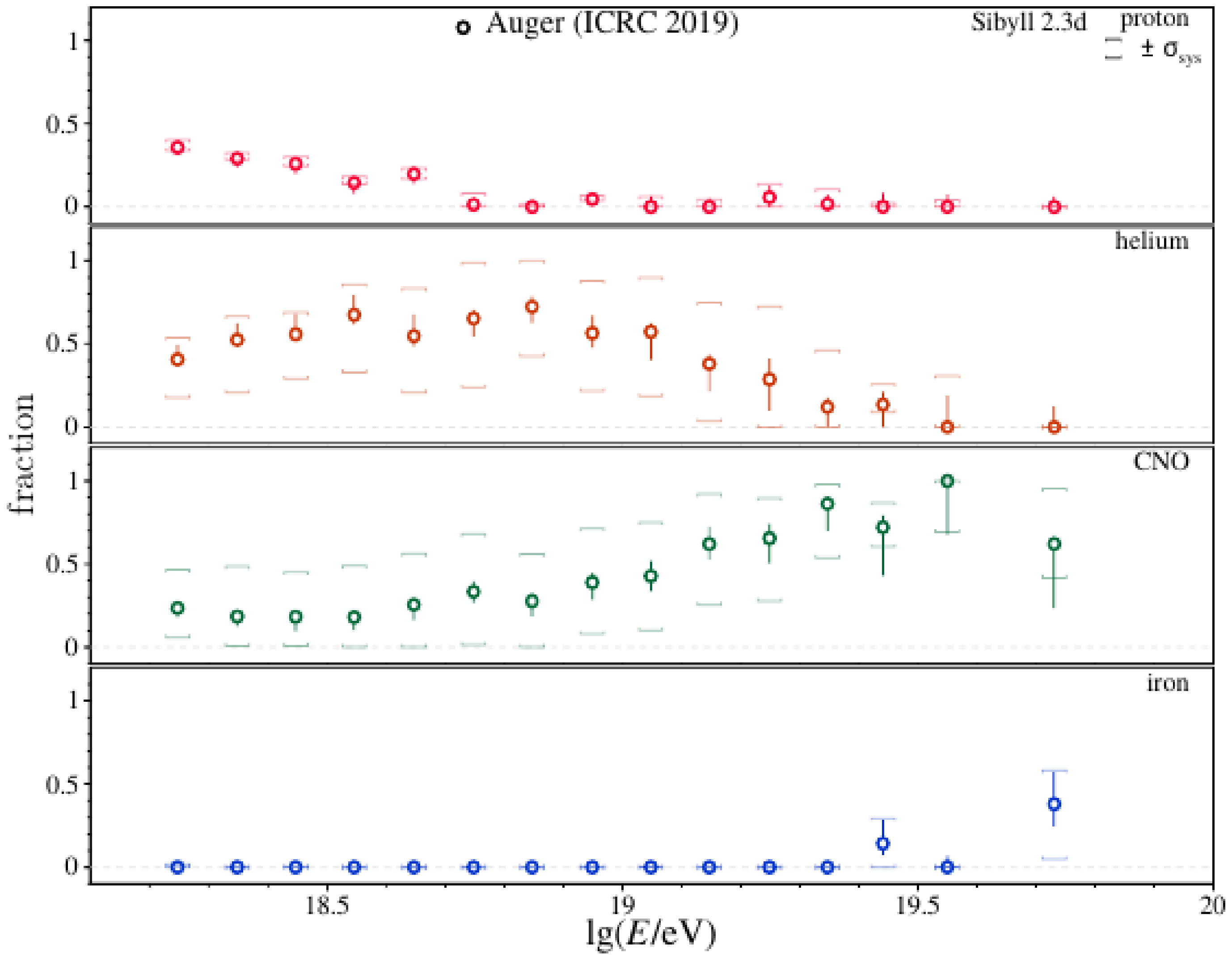
UHECR mass composition comparison between TA and Auger: composition Working Group

Method to transfer Auger data into TA detector

Combine (p, He, N, Fe) of Sibyll 2.3d to fit Auger X_{max} distributions



Energy evolution of nuclear fractions in fits of the Auger X_{max} distributions



Use as a proxy simulated X_{max} mixes (AugerMixes) and process them with the TA machinery

Result: AugerMixes ⊗ TA — representation of Auger X_{max} distributions folded with the TA detector and analysis effects

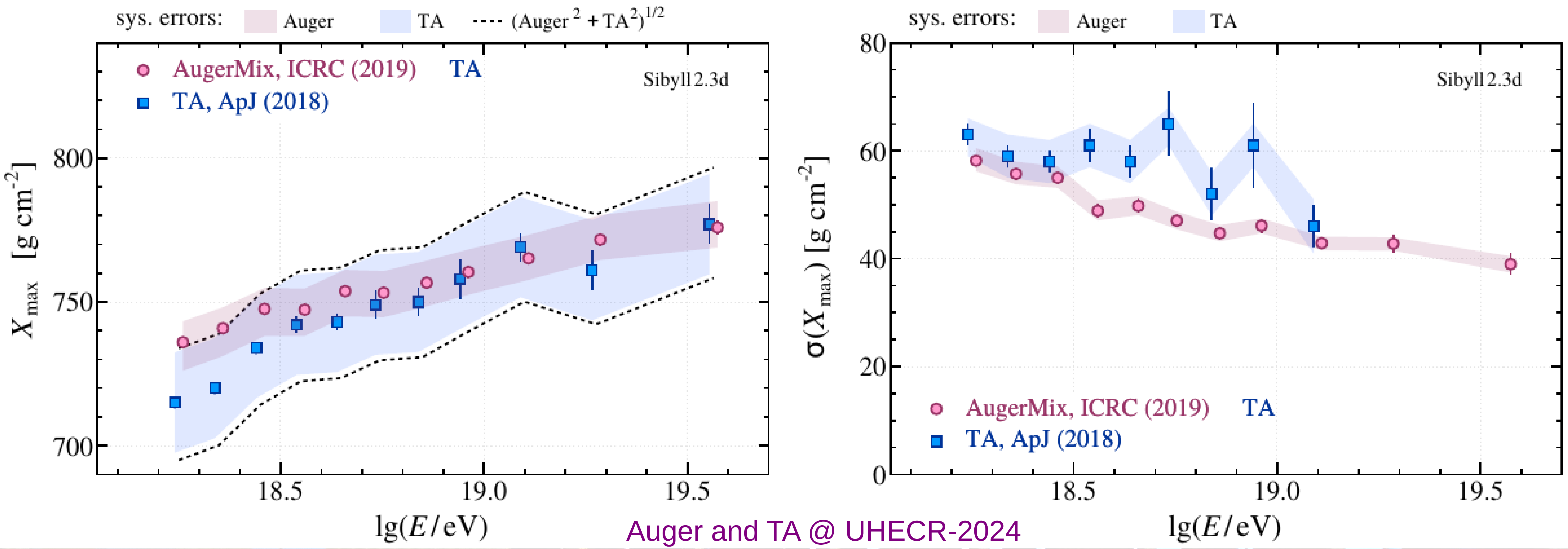
Comparison of the X_{max} moments measured at TA and Auger $\otimes$ TA

$\langle X_{max} \rangle$ — agreement withing statistical and systematic uncertainties, in particular for $\lg(E/\mathrm{eV}) > 18.5$

$\sigma(X_{max})$ — larger values in TA for $\lg(E/\mathrm{eV}) = 18.5 - 19.0$, possible reasons:

◇ constant aerosol profiles used in TA increase $\sigma(X_{max})$ by 18.9 $\mathrm{g\,cm^{-2}}$ (in quadrature) [ApJ 858 (2018) 76]

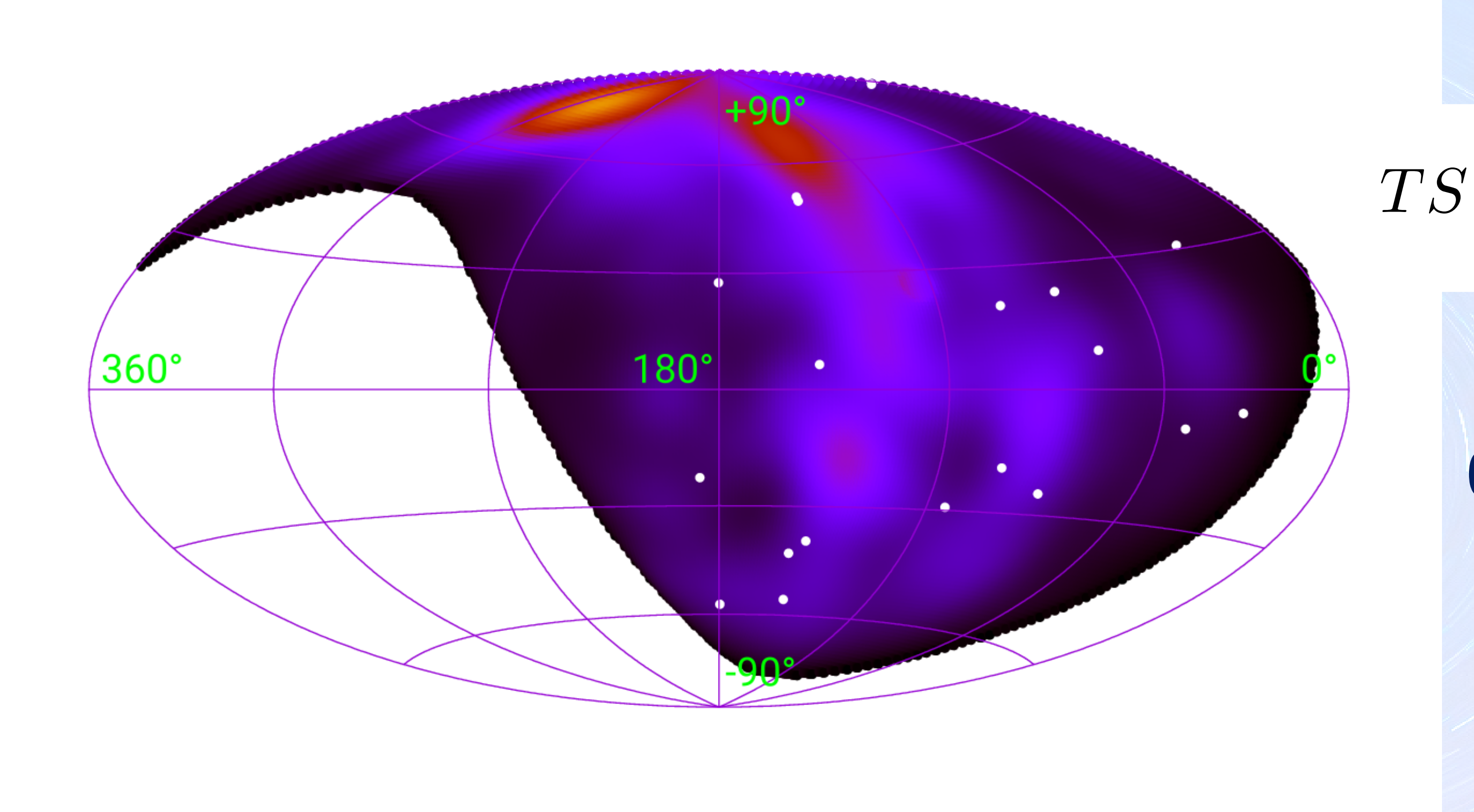
◇ a few deep events in data can increase $\sigma(X_{max})$ significantly (see X_{max} distributions in next slides)



Auger and TA @ UHECR-2024

- No full agreement
- Auger mix for TA analysis is tested, but the inverse test is also needed!

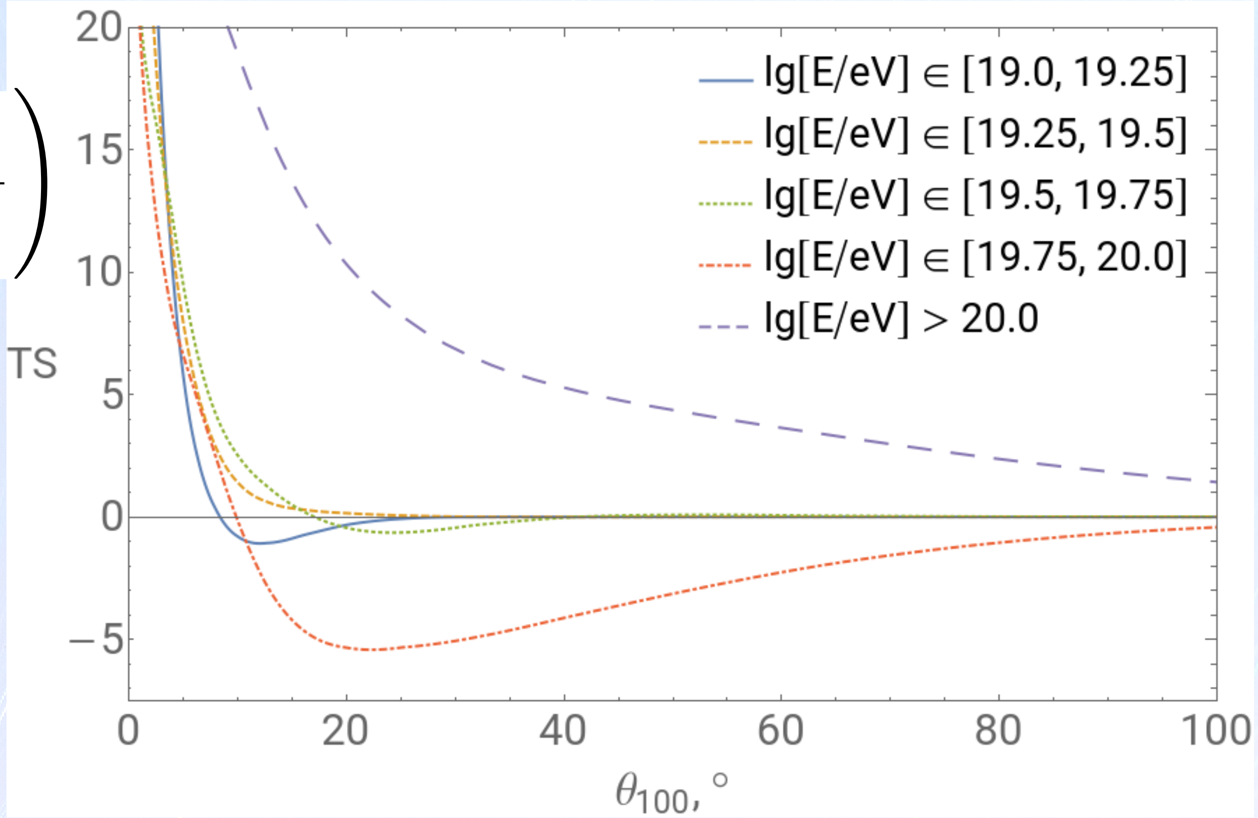
UHECR mass composition from arrival directions distribution



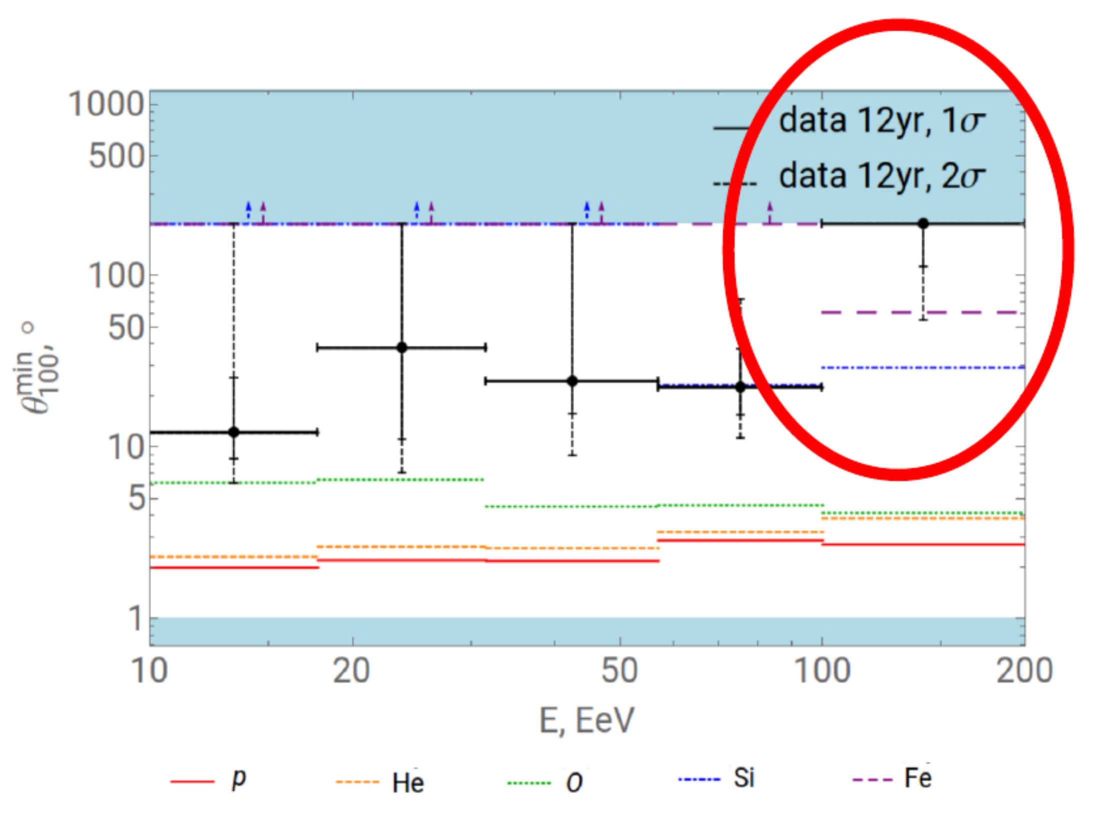
Map of expected UHECR flux + data at E > 100 EeV

$$TS(\theta) = -2\sum_{E_k}\left(\sum_i \ln\frac{\Phi_{E_k}(\theta, \mathbf{n}_i)}{\Phi_{\mathrm{iso}}(\mathbf{n}_i)}\right)$$

θ: average UHECR deflection from sources (galaxies)



Compare with UHECR simulations

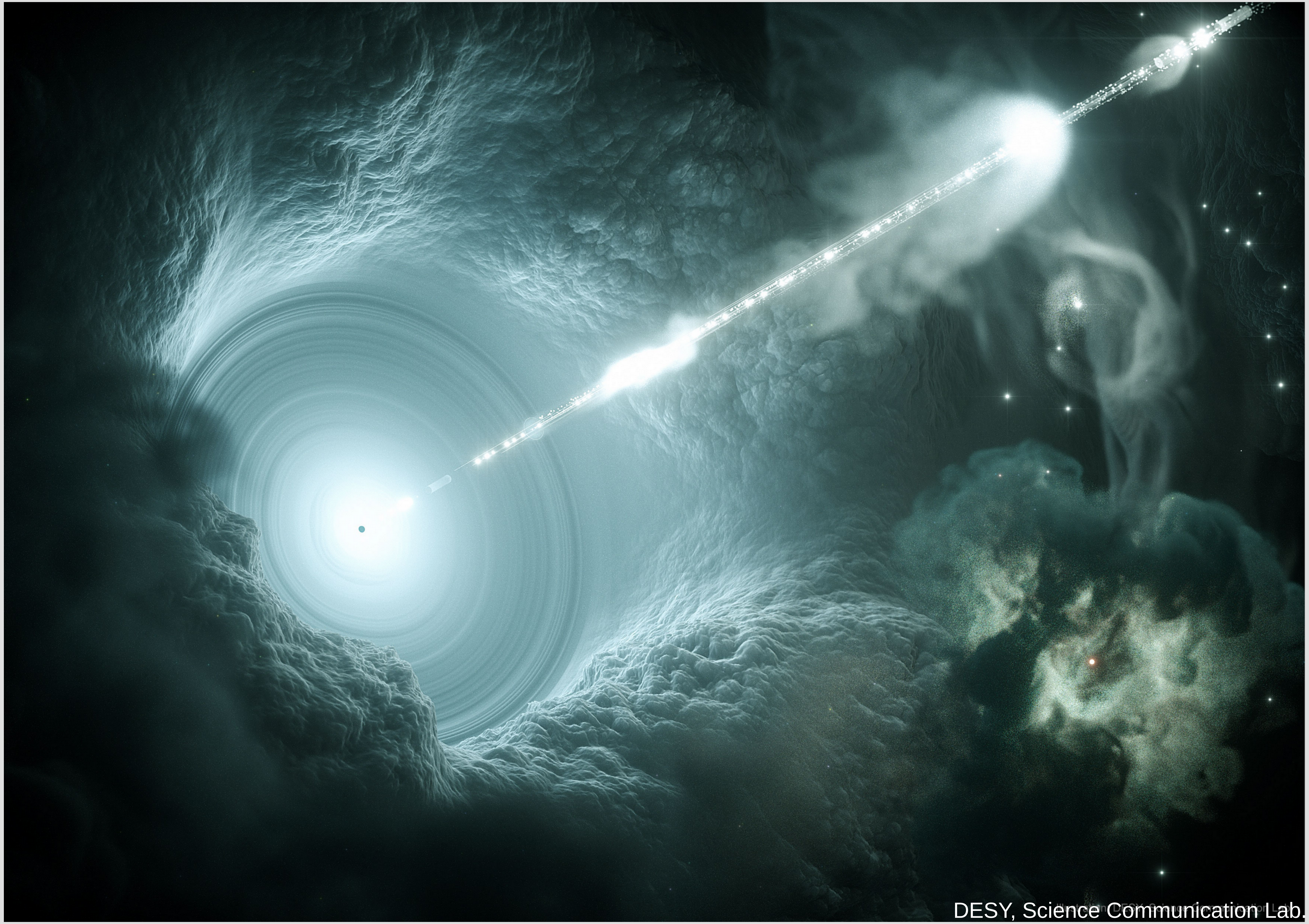


For E > 100 EeV CR are very isotropic — evidence of very heavy composition at these energies

The results are robust to various uncertainties of UHECR flux model

TA,
PRL 133, 041001 (2024)
PRD 110, 022006 (2024)

UHECR anisotropy and search for sources



DESY, Science Communication Lab.

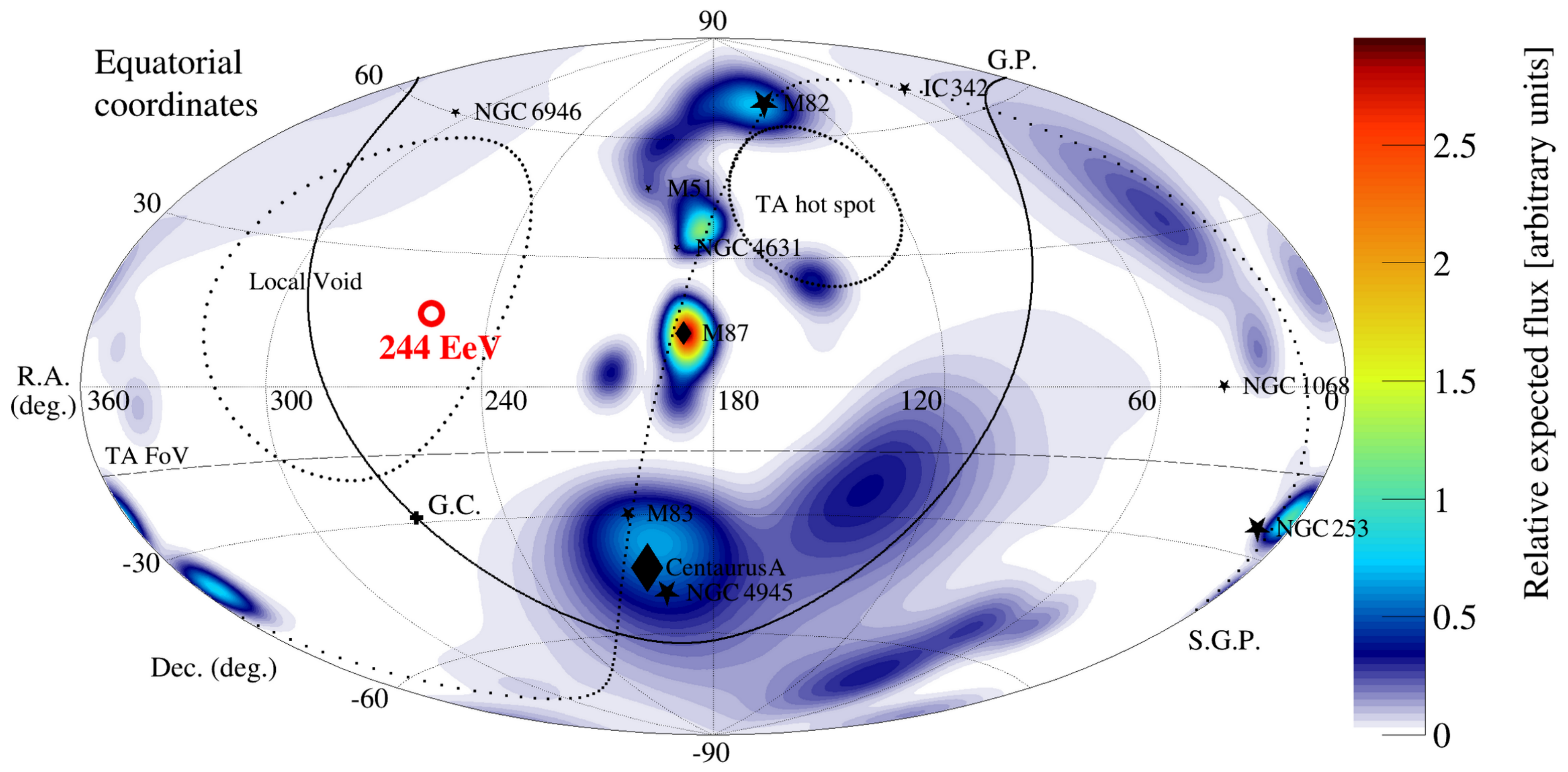
Extreme energy particle

Date (UTC)	Energy (EeV)	S_{800} (m^{-2})	Zenith angle	Azimuth angle	Right Ascension	Declination
27 May 2021 10:35:56	244 ± 29(stat.) $^{+51}_{-76}$ (syst.)	530 ± 57	$38.6 \pm 0.4°$	$206.8 \pm 0.6°$	$255.9 \pm 0.6°$	$16.1 \pm 0.5°$

Particle type

- No FD observations (X_{max})
- SD analysis with machine learning
  - Gamma-ray is rejected **3.8σ**
  - Not possible to distinguish nucleus type

TA, Science 382 (2023) 903



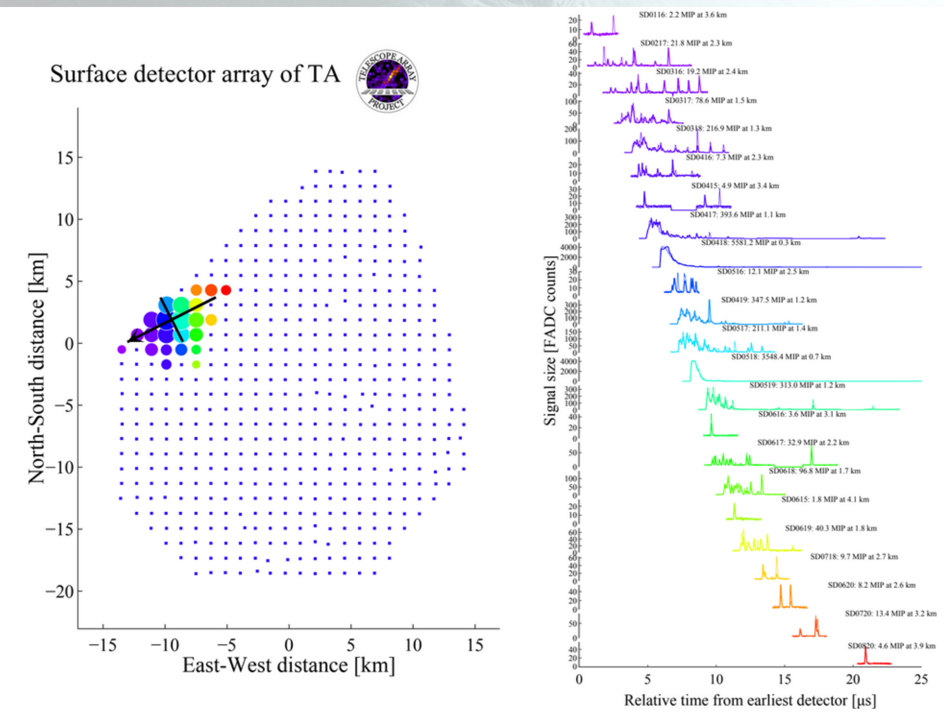
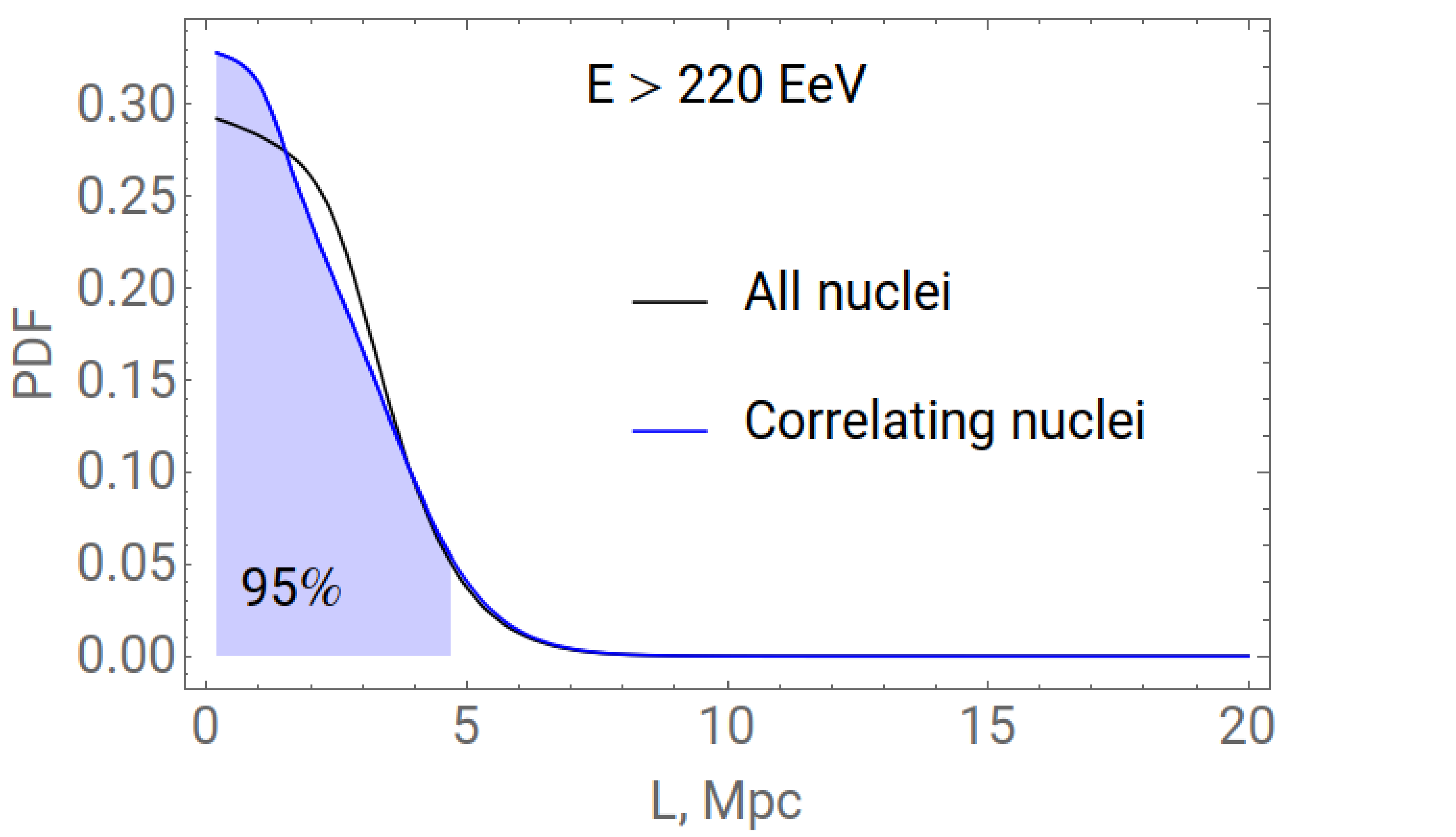


Illustration: DESY, Science Communication Lab

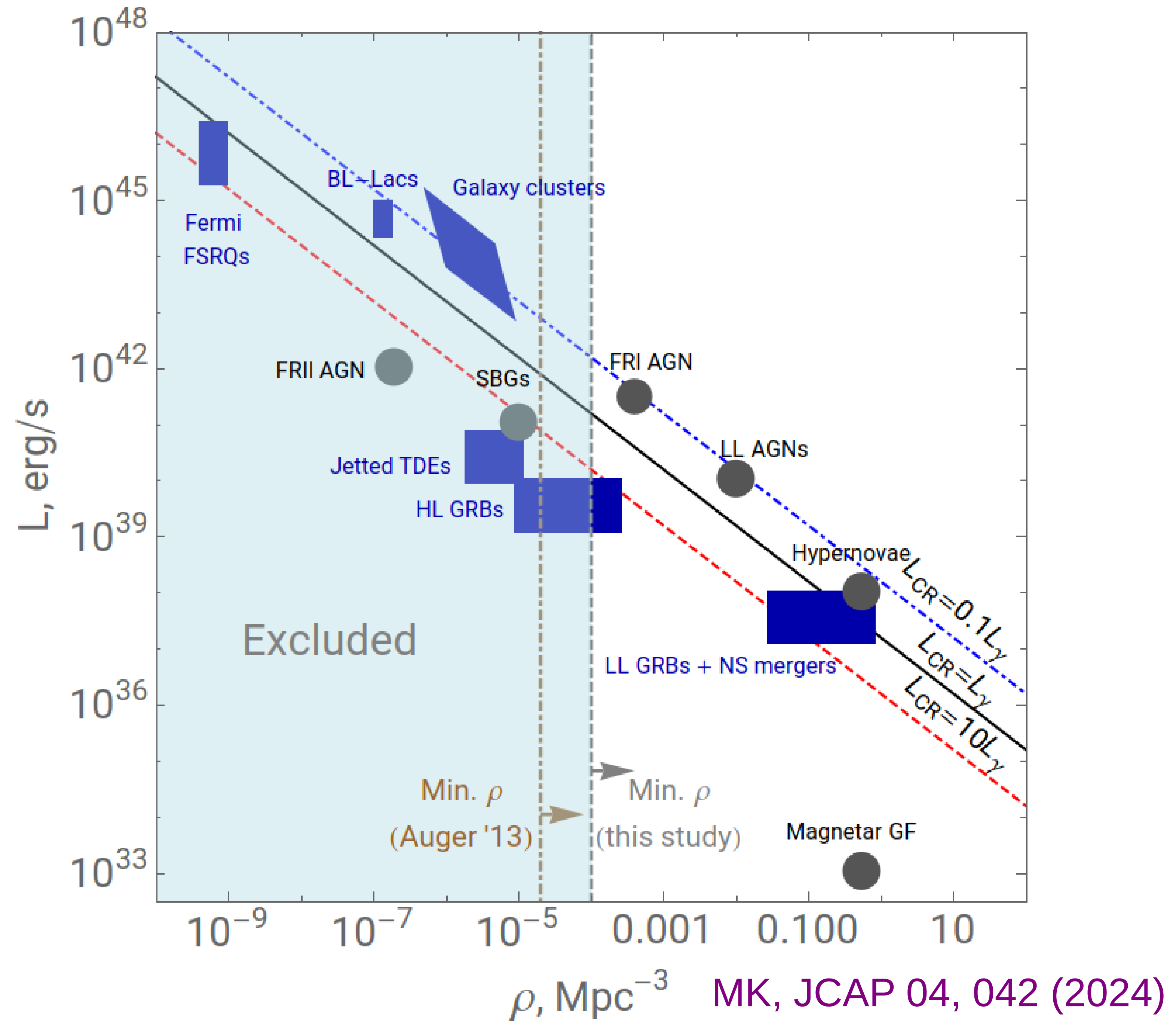
Constraints on closest UHECR source and source number density

For highest energy particles the attenuation length is small – the source should be close



In basic model
(injected Fe, E = 220 EeV, weak EGMF)
L < 4.7 Mpc (95% C.L.)

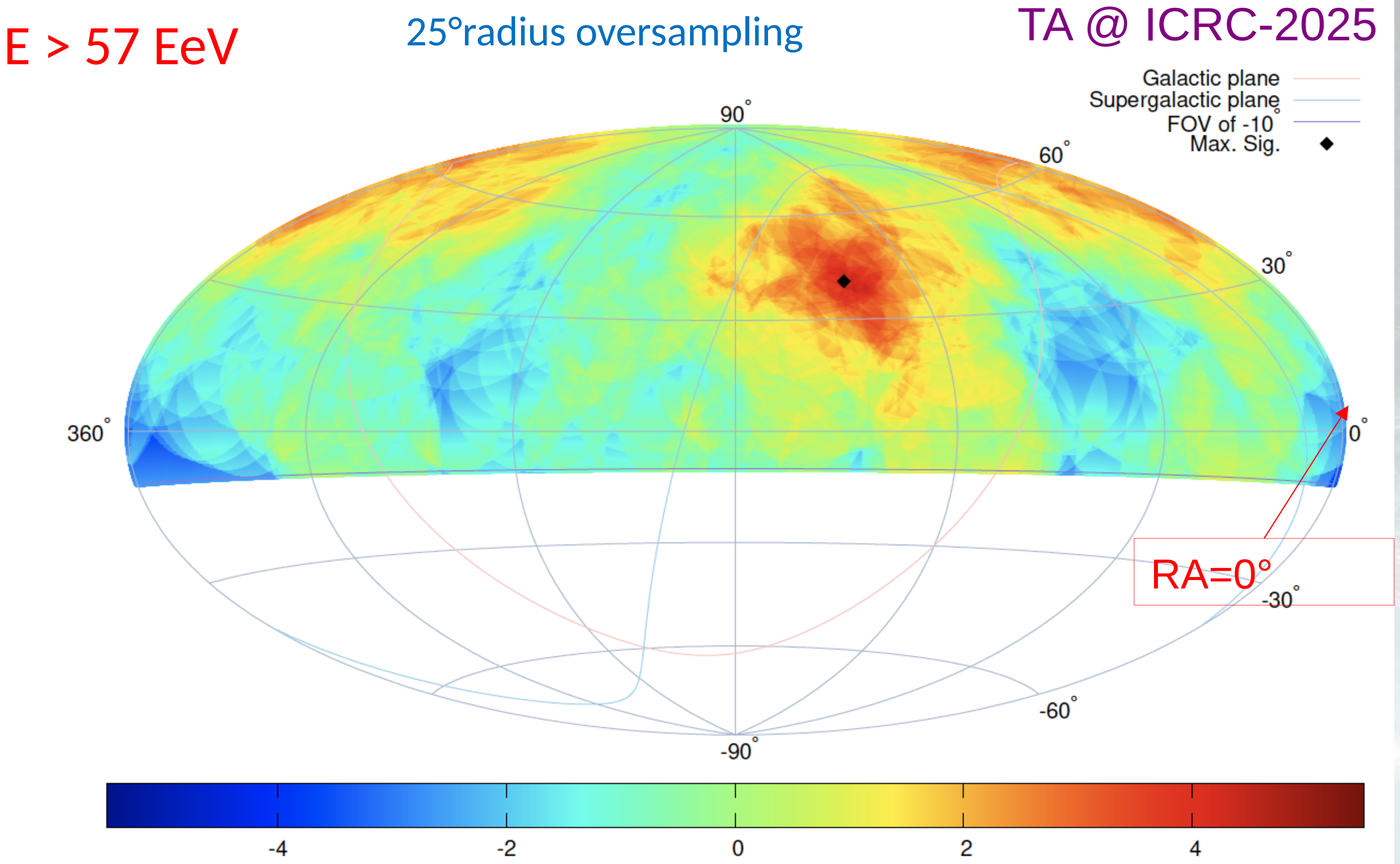
$\rho_{source} > 1.0 \cdot 10^{-4}$ Mpc^{-3}

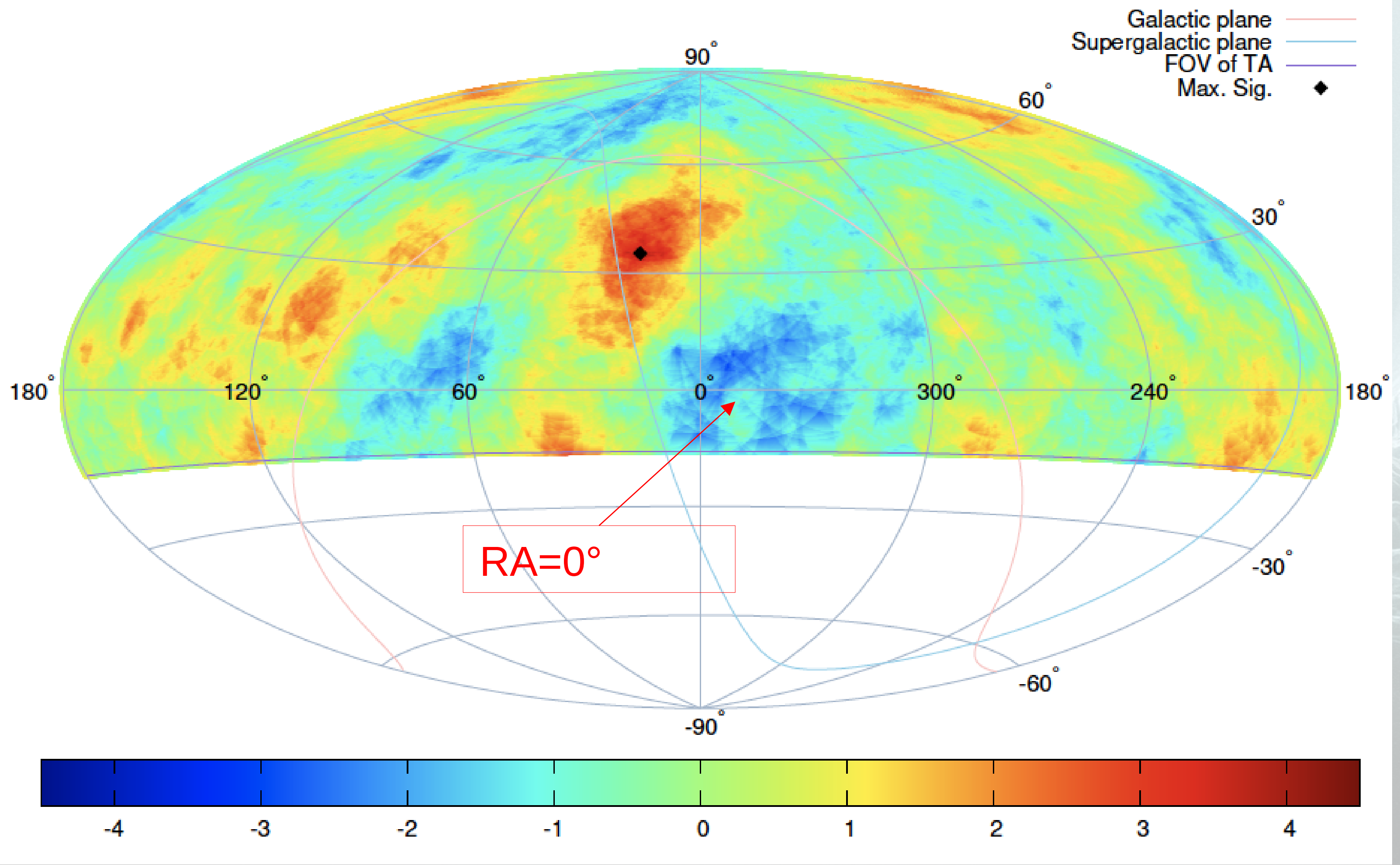


MK, JCAP 04, 042 (2024)

Constraints for sources emitting heavy UHECR are set for the first time

Illustration: DESY, Science Communication Lab





Intermediate-scale anisotropy: Hotspot and a PPSC excess

Analysis method:

- Oversample number of UHECR events within a fixed radius circle from each direction.
- Evaluate Li-Ma significance from isotropy expectation.
- TA SD data collected over 15 years was used.

Hotspot (E > 57 EeV):

- 228 events
- max. local significance: 4.9σ at (144.0°, 40.5°)
- global significance: **2.9σ**

The Perseus-Pisces super cluster (PPSC) excess (E > $10^{19.4,\ 19.5,\ 19.6}$ eV):

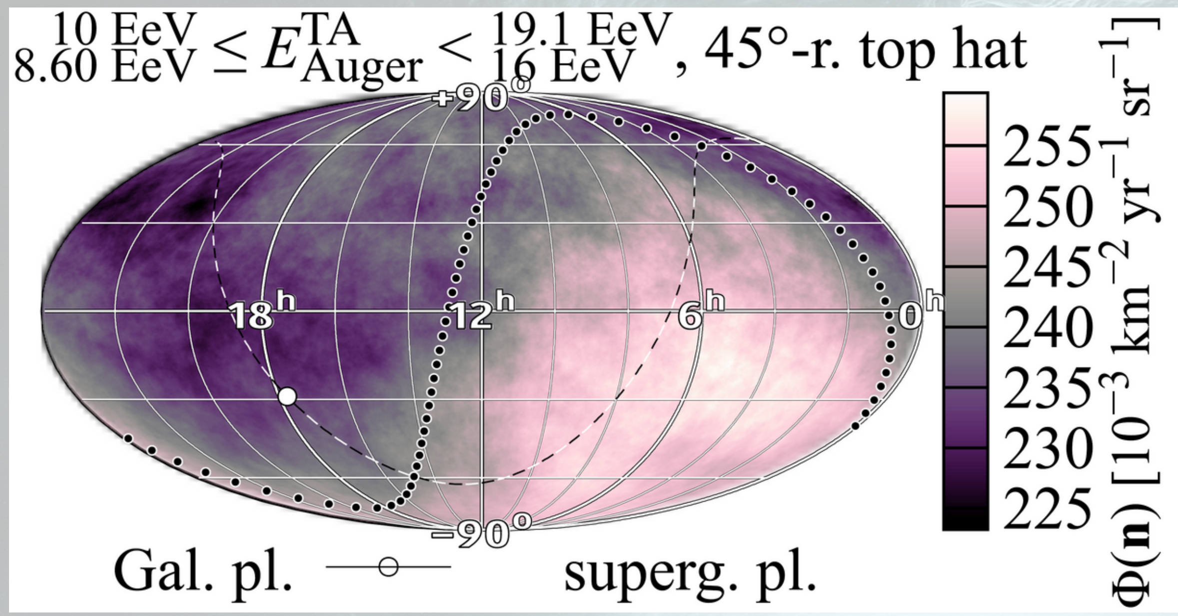
- 1186, 767, 464 events
- significances: **3.1σ, 3.2σ, 3.0σ**

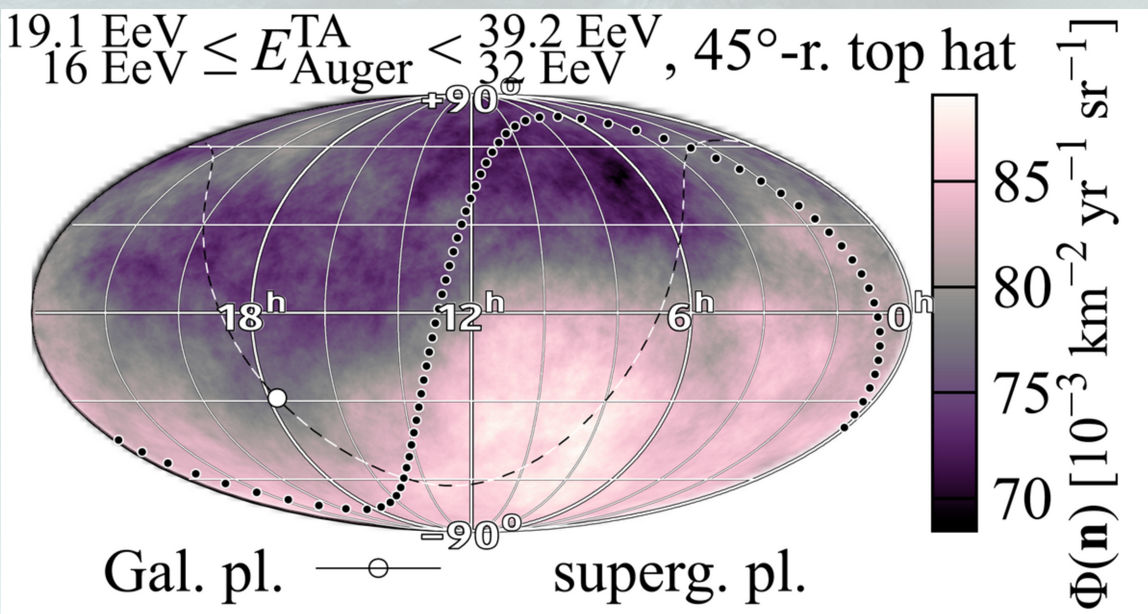
Illustration: DESY, Science Communication Lab

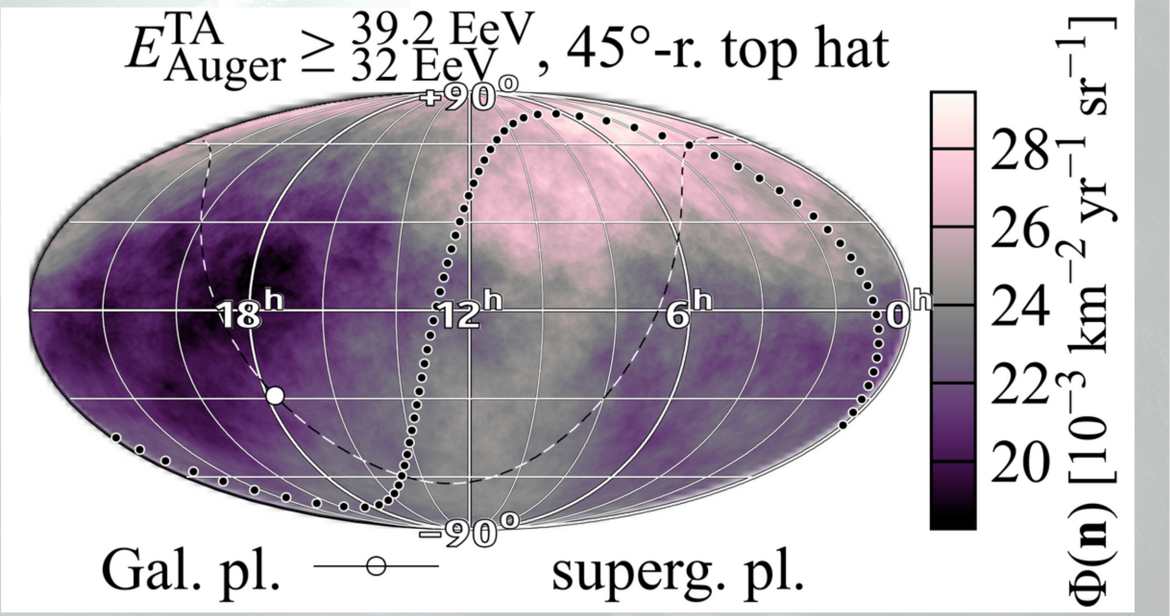
Large scale anisotropy in full sky (harmonic amalysis)

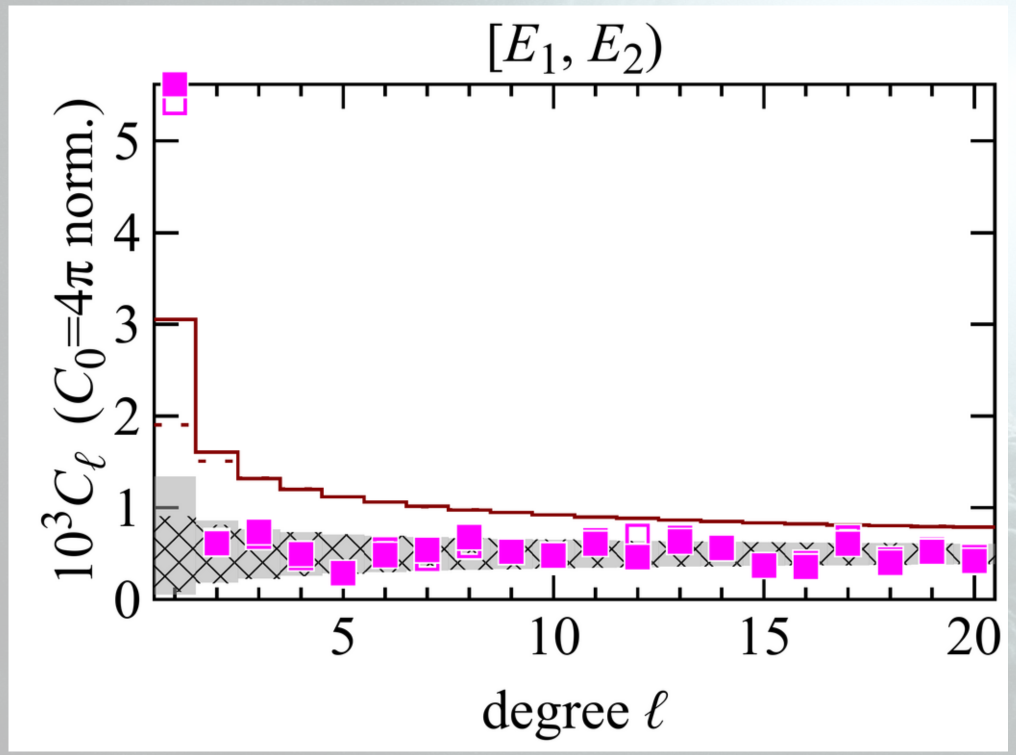
Auger + TA anisotropy Working Group

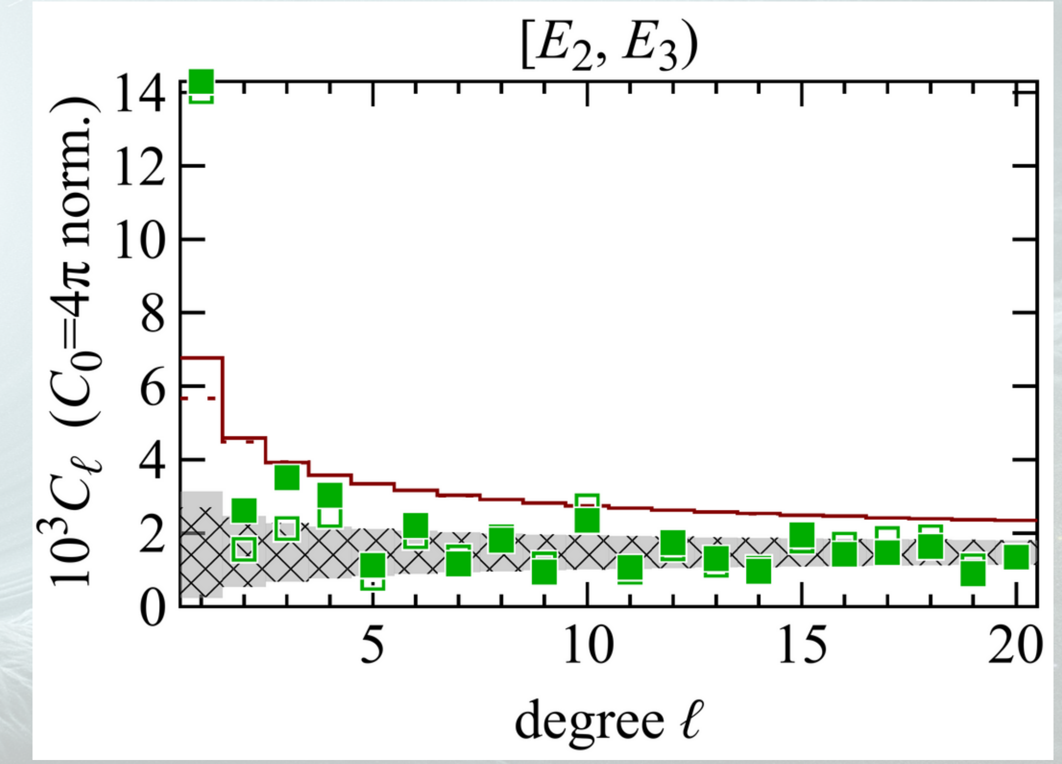
Auger and TA @ ICRC-2025

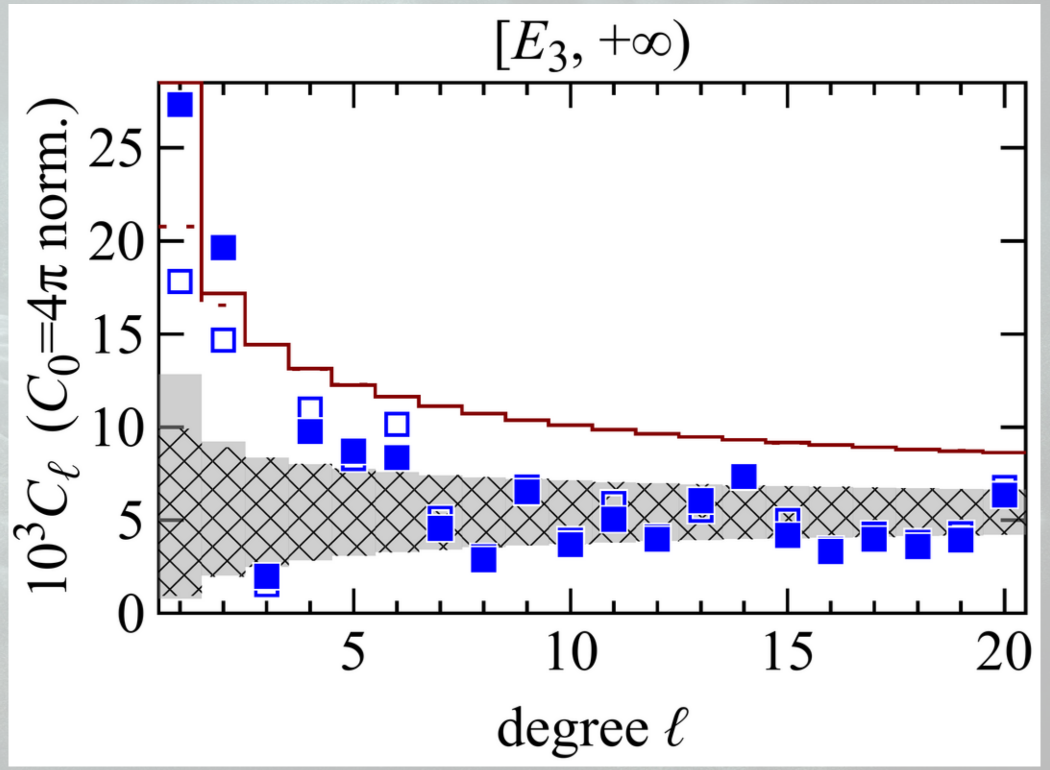












- Significant dipole: amplitude is growing with energy (pointing outside the Galaxy)
- First evidence of quadrupole (at E > 40 EeV): in line with LSS models predictions

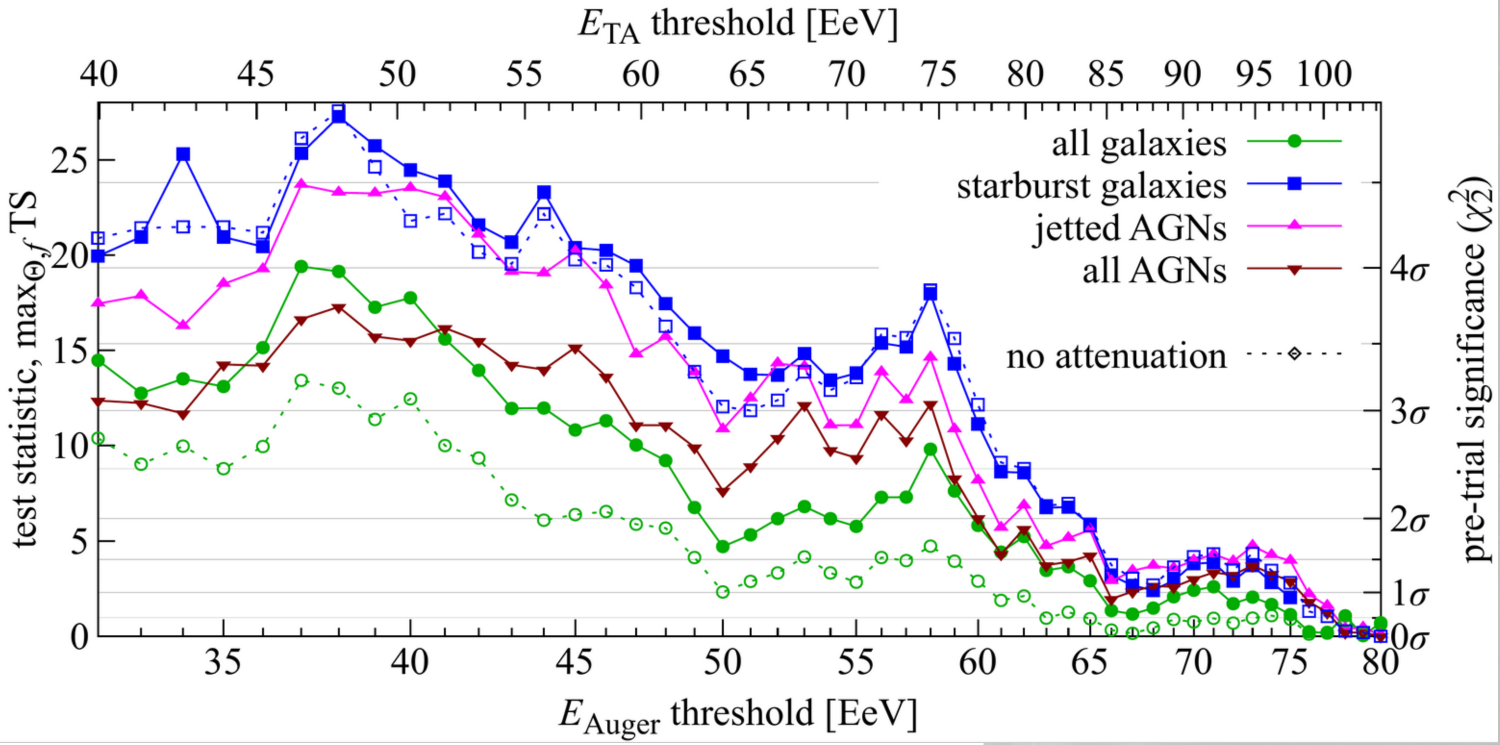
Illustration: DESY, Science Communication Lab

Search for UHECR correlation with sources in full sky

Auger + TA anisotropy Working Group

Auger and TA @ ICRC-2025

	N of objects	Distances	Wavelength
All galaxies	> 44000	1 Mpc to 250 Mpc	Infrared (2.16 μm)
Starburst galaxies	44	1 Mpc to 130 Mpc	Far- Infrared (60 mm) Radio (1.4 GHz)
All AGNs	523	1 Mpc to 250 Mpc	X-ray (14–195 keV)
Jetted AGNs	26	1 Mpc to 250 Mpc	γ-ray (10 GeV–1 TeV)



Correlation with all galaxies $1\,\mathrm{Mpc} \leq D < 250\,\mathrm{Mpc}$ (2MRS catalog)

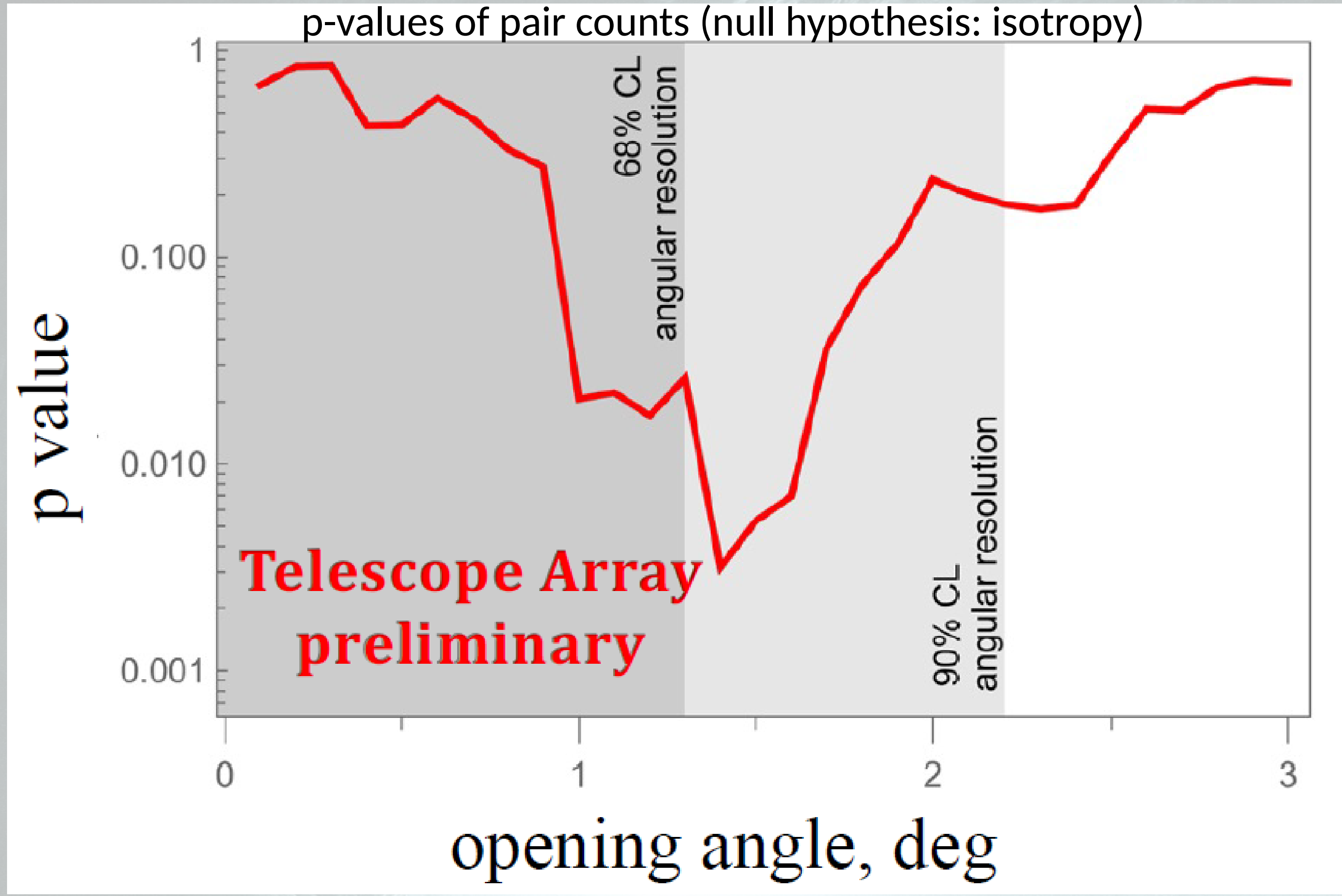
dataset	E^{min}_{Auger}	E^{min}_{TA}	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$\left(19^{+15}_{-7}\right)^\circ$	$\left(25^{+24}_{-10}\right)\%$	14.7	2.8σ
UHECR 2024	37 EeV	46.5 EeV	$\left(26^{+13}_{-15}\right)^\circ$	$\left(30^{+26}_{-17}\right)\%$	13.5	2.6σ
ICRC 2025	37 EeV	47 EeV	$(29.2^{+12.9}_{-17.5})^\circ$	$(33.6^{+26.3}_{-19.4})\%$	13.5	2.8 σ

Correlation with starburst galaxies $1\,\mathrm{Mpc} \leq D < 130\,\mathrm{Mpc}$ (Lunardini+ '19 catalog)

dataset	E^{min}_{Auger}	E^{min}_{TA}	Θ	f	TS	post-trial
ICRC 2023	38 EeV	48.2 EeV	$\left(15.4^{+5.2}_{-3.0}\right)^\circ$	$\left(11.7^{+4.7}_{-2.9}\right)\%$	30.5	4.6σ
UHECR 2024	38 EeV	47.8 EeV	$\left(15.0^{+5.0}_{-2.9}\right)^\circ$	$\left(11.1^{+4.4}_{-2.8}\right)\%$	29.5	4.4σ
ICRC 2025	38 EeV	48 EeV	$(15.0^{+4.8}_{-2.9})^\circ$	$(10.6^{+4.0}_{-2.7})\%$	27.3	4.2 σ

Illustration: DESY, Science Communication Lab

UHECR anomalous correlation with BL Lac objects (TA only)



- Likelihood analysis was conducted to confirm the correlation with BL Lac objects reported by the HiRes Collaboration; suggesting the presence of a small fraction of neutral primaries at E > 10 EeV.
- 6712 TA SD events
- Post-trial p-value with pair counting method **3.0×10^{-2}** for events with **E > 10 EeV**
- P-value with maximum likelihood method **1.7×10^{-3}** for events with **E > 10 EeV**
- P-value with maximum likelihood method **3.3×10^{-3}** for events with **E > 1 EeV**
- **Correlating fraction is ~0.7%**

Likelihood analysis results

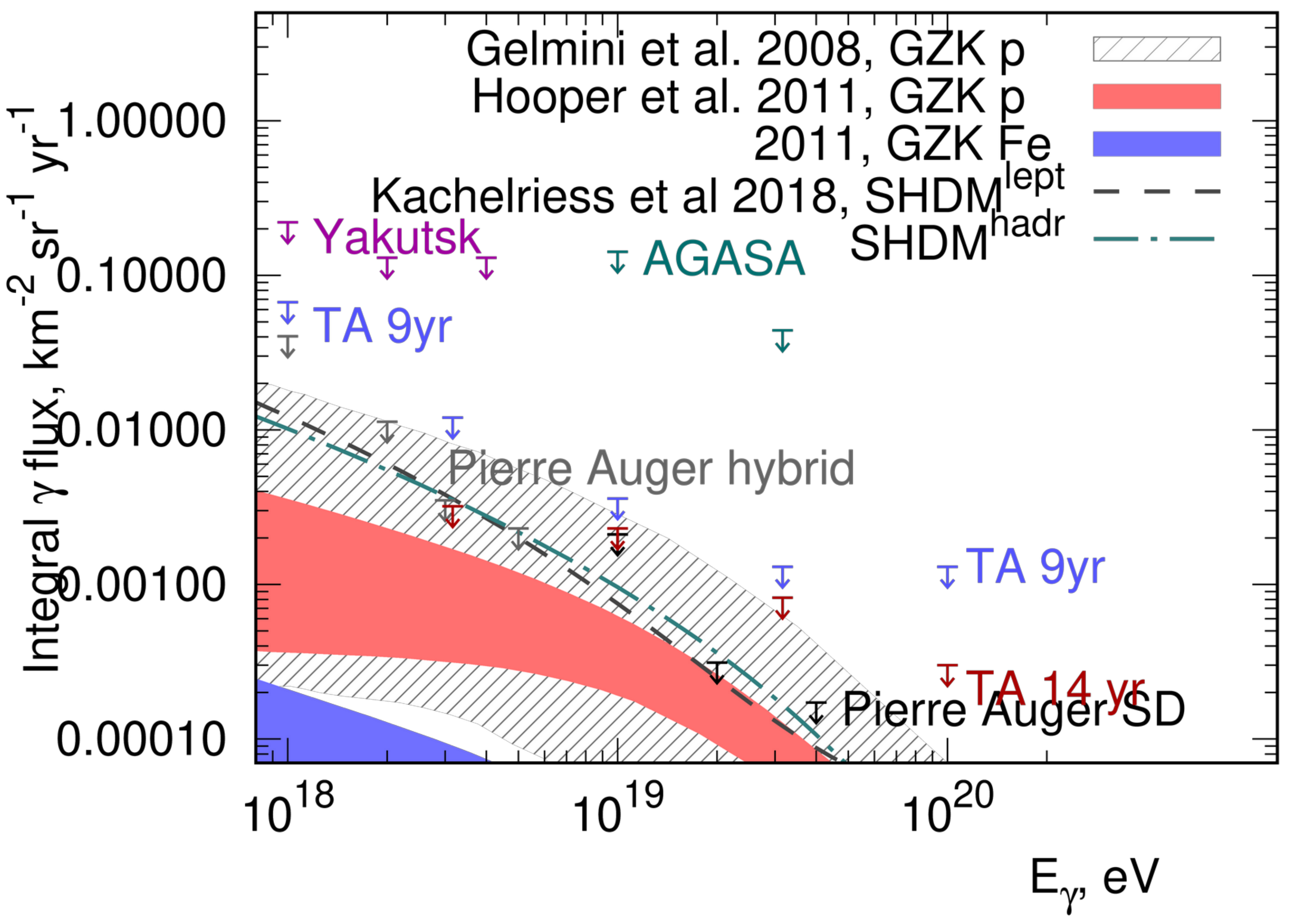
E, eV	$\ln(\mathcal{R})$	n_s	$<\ln(\mathcal{R})>$	$\sigma_{\ln\mathcal{R}}$	$<n_s>$	$\mathcal{F}$
$E \geq 10^{19}$	29.23	100	9.50	4.85	56.41	$\mathbf{1.7\times10^{-3}}$
$E \geq 10^{18}$	61.19	616	34.03	8.91	482.63	$\mathbf{3.3\times10^{-3}}$

TA @ ICRC-2025

…tion: DESY, Science Communication Lab

Search for UHE gamma-rays

Telescope Array @ UHECR-2024

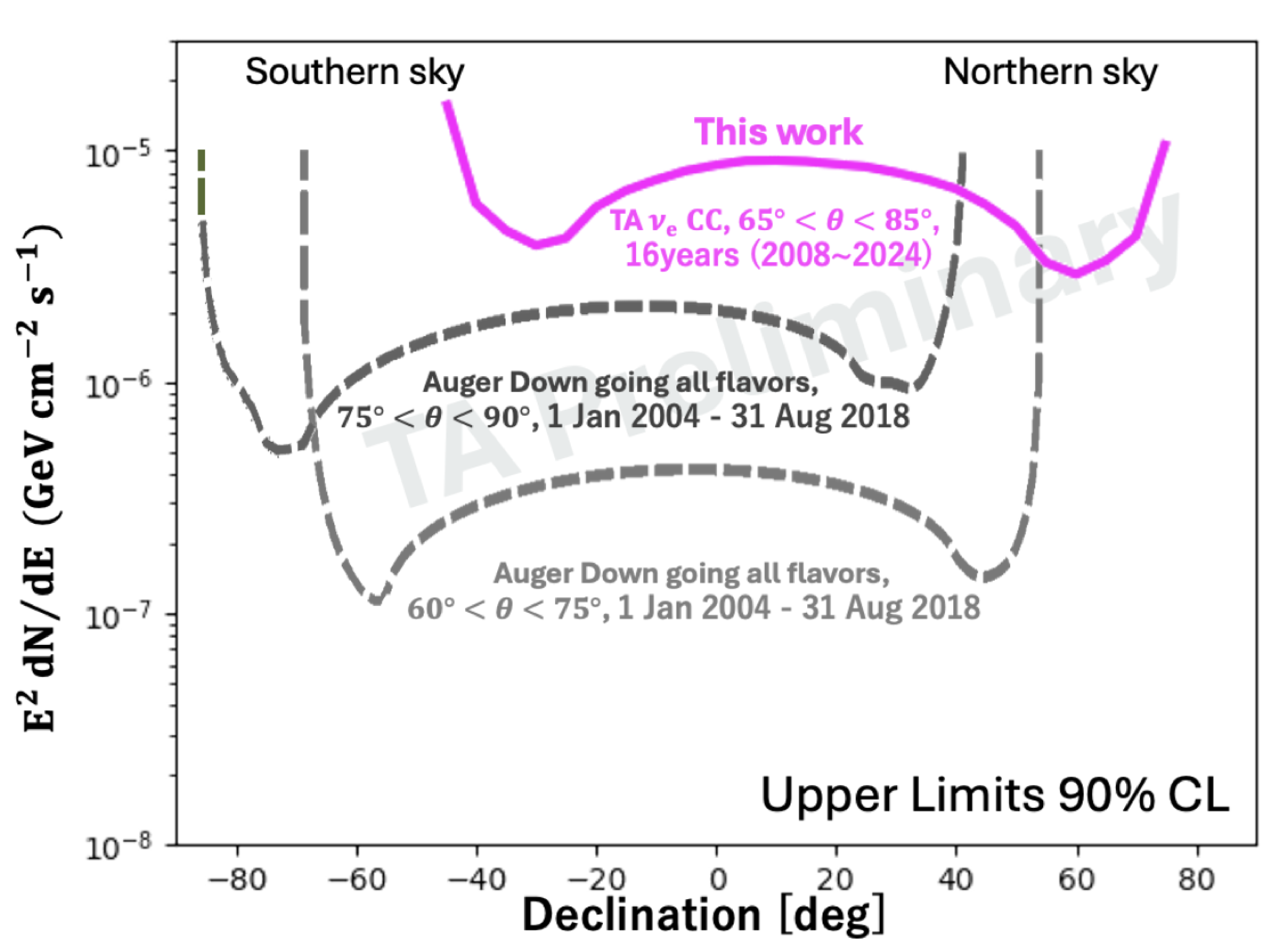


- A neural network classifier is developed and trained on the photon-induced and proton-induced Monte-Carlo event sets.
- A classifier is fine-trained using the data events which are not photons with high confidence.
- The limits on the ultra-high-energy photon flux are established based on 14 years of TA SD data.
- Limits are competitive with Auger at $E > 10^{18.5}$ eV
- The limits probe the protonic models for cosmogenic UHE gamma

Illustration: DESY, Science Communication Lab

Search for UHE neutrinos

Telescope Array @ ICRC-2025



- Upper limits on UHE neutrinos are obtained with 16 years TA SD data.
- Inclined shower events : 65°< θ <85°
- Two observables
  – Shower curvature parameter
  – Area over peak

No neutrino event was observed (N_{exp} = 2.44).

Illustration: DESY, Science Communication Lab

Conclusions

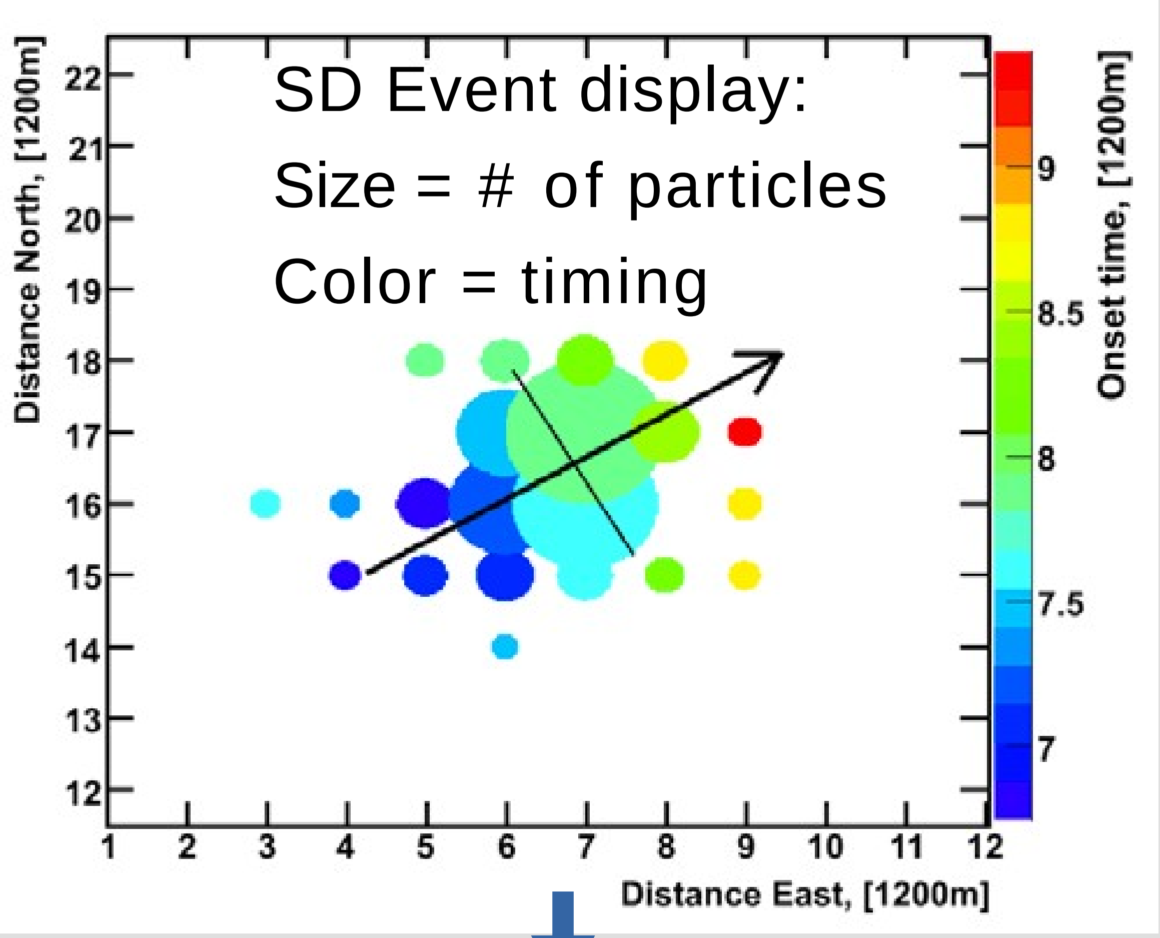
- New «shoulder» feature (softening) in all-particle UHECR spectrum at E ≈ 14 EeV
- TA and Auger spectra are not consistent in common sky-band at highest energies
  - Tension can be alleviated by cutting-off excess areas in TA
- TA and Auger spectra are severely inconsistent in their full FoV (8σ)
  - Possible evidence for distinct UHECR source in the Northern sky
- TA FD measurements consistent with protons up to highest energies
  - Not fully consistent with Auger-inferred composition
- Evidence of very heavy injected UHECR composition at highest energies (E > 100 EeV) from distribution of arrival directions and flux simulations
- Extreme energy (244 EeV) particle is detected
  - The closest UHECR source should be not farther than 5 Mpc
  - Sources in general are not rarer than 10^{-4} Mpc^{-3}
- TA Hotspot at E > 57 EeV is persisting
- Auger-TA UHECR – starburst galaxies correlation is persisting
- First evidence of arrival directions quadrupole at E > 40 EeV
- Evidence of anomalous correlation of small fraction of UHECR with distant BL Lacs

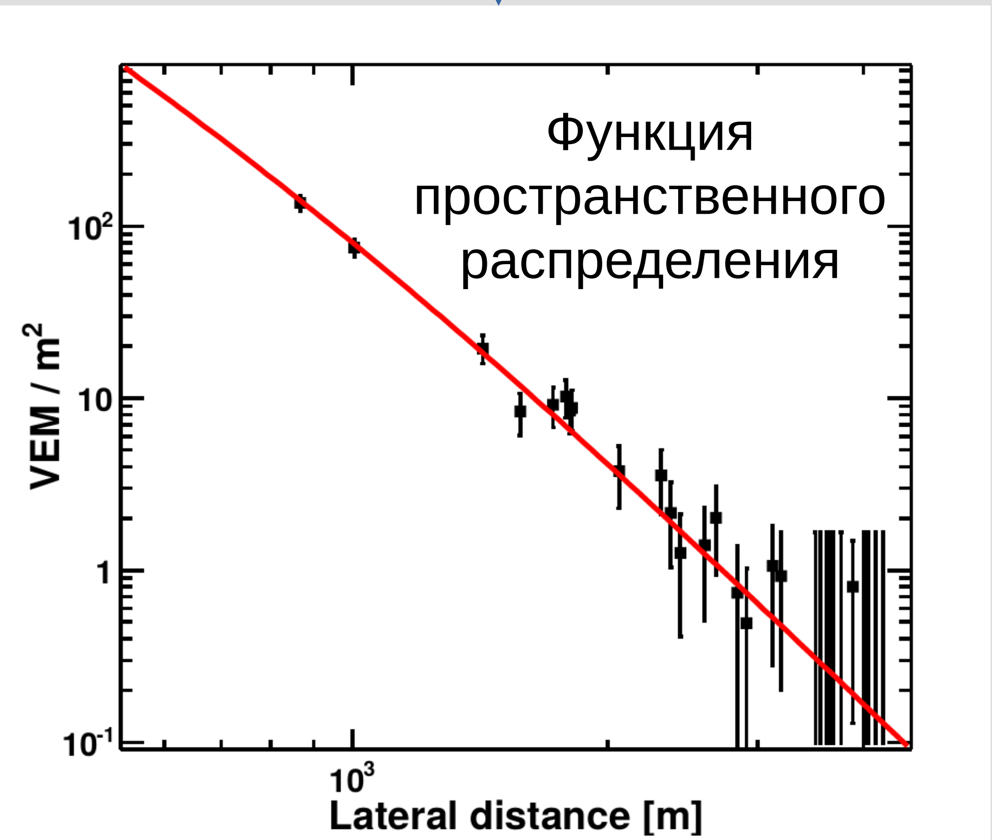
Thank you!

Backup slides

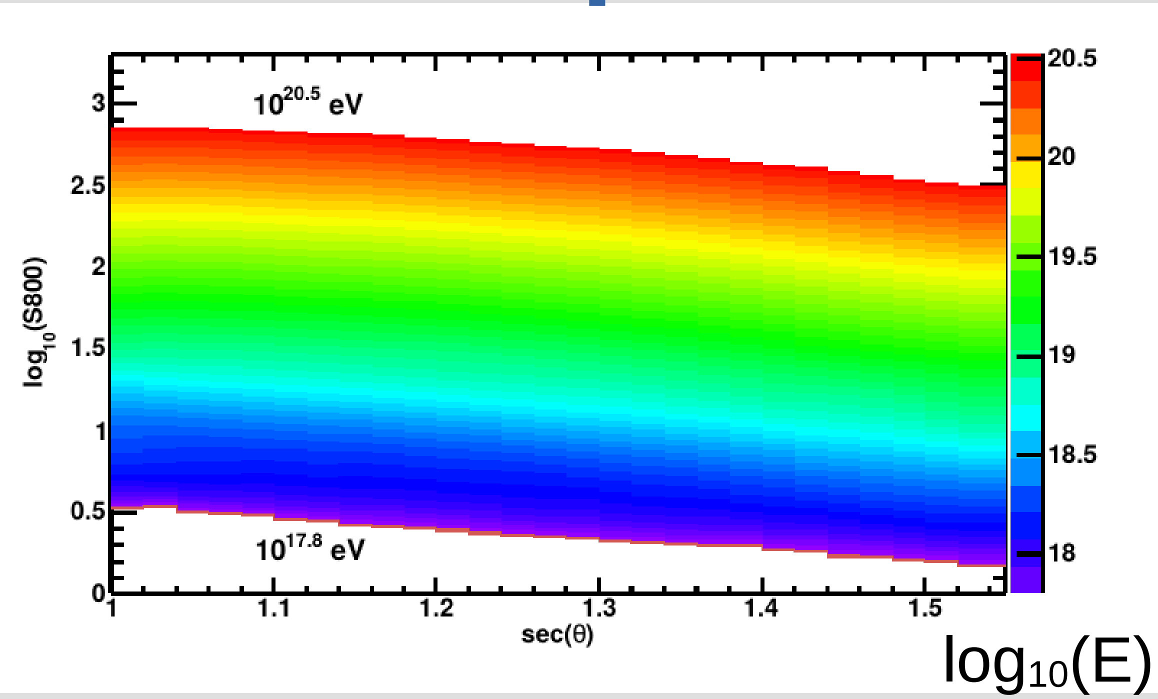
Реконструкция наземного события

Реконструкция флуоресцентного события





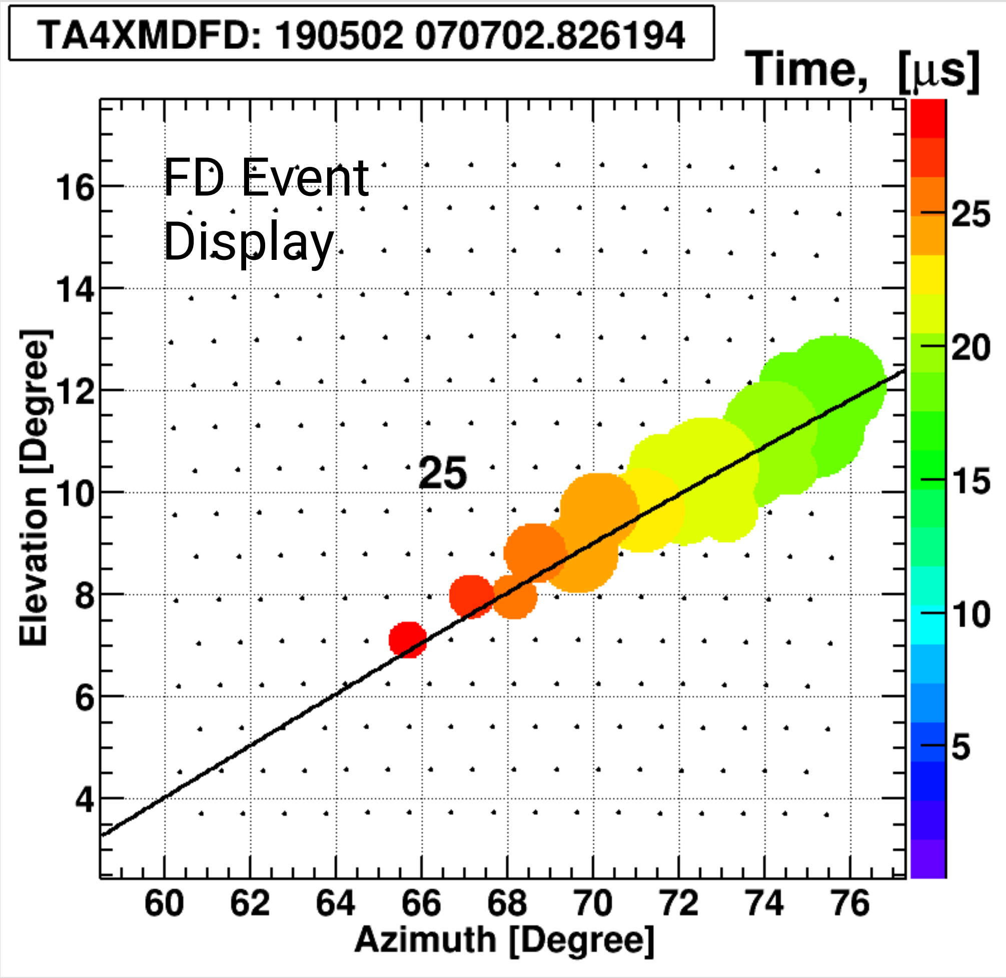
E = E (ρ_{800},θ)



$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

s — расстояние до оси ливня
θ — зенитный угол



SD энергия перешкалируется к более точному FD масштабу

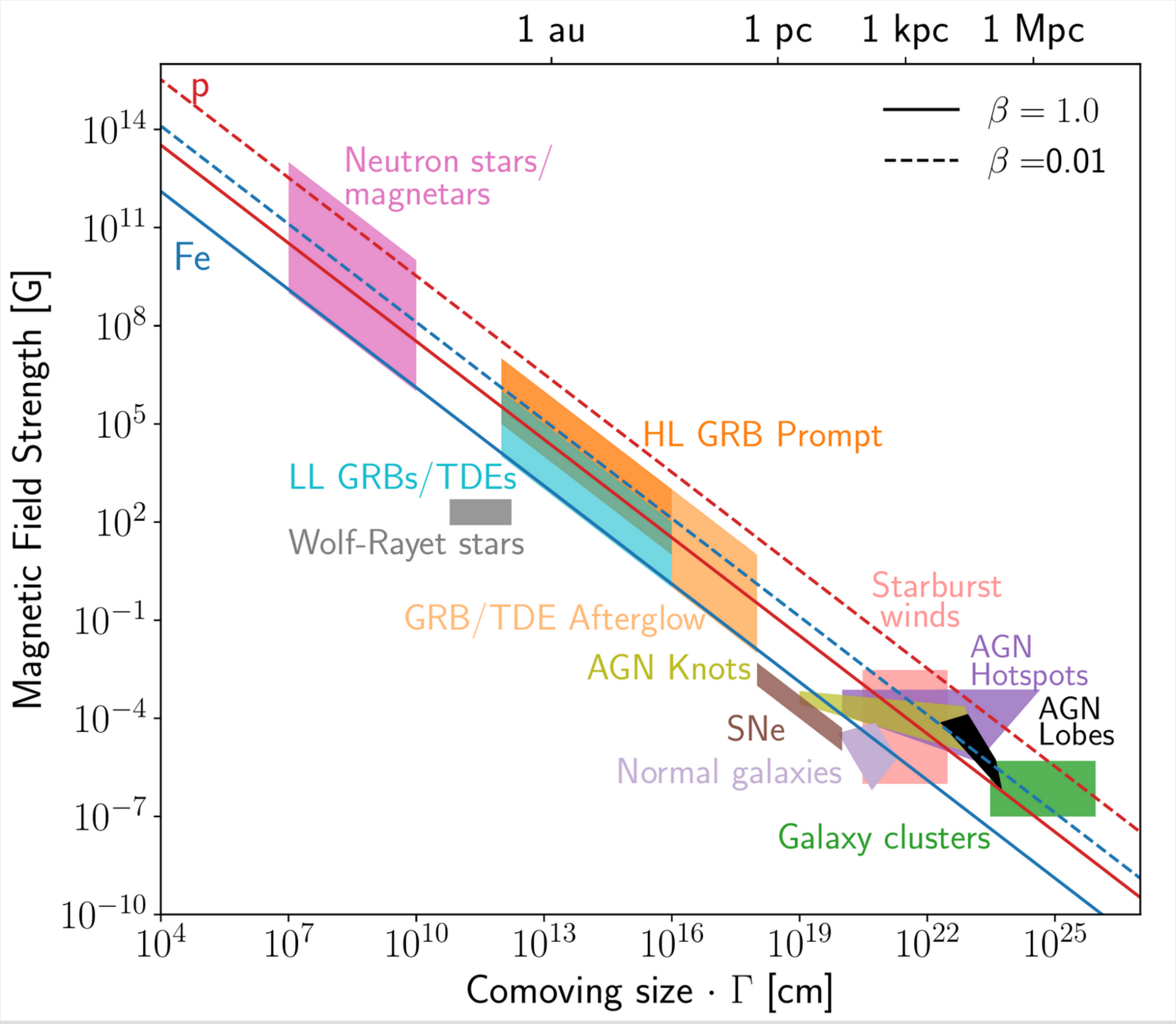
$E_{final} = E_{SD} / 1.27$

Ускорение КЛ в их возможных источниках

Критерий Хилласа

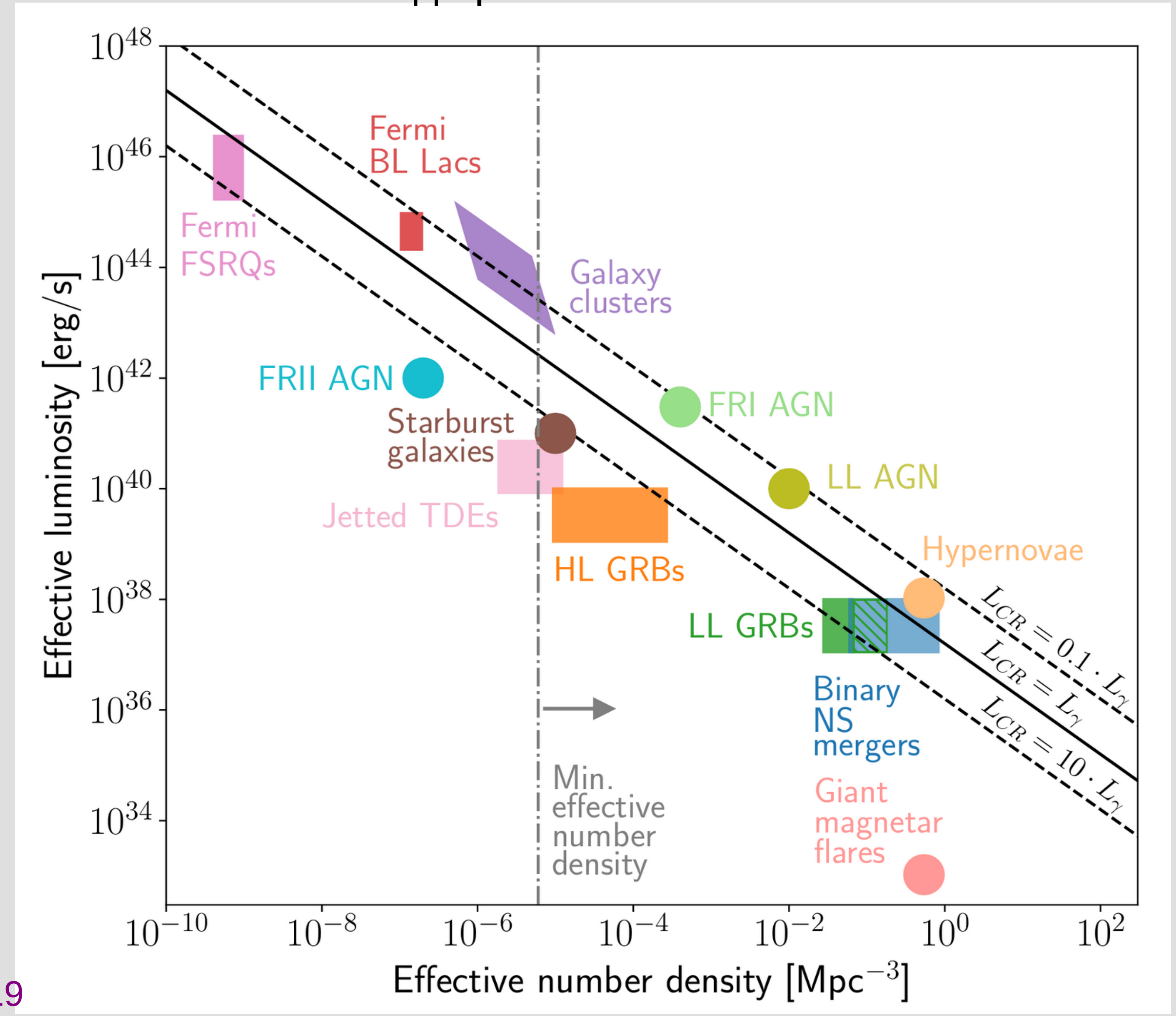
R = E/qB — ларморовский радиус
$E_{max} = \beta_{shock} q B R \Gamma$ — максимальная достижимая энергия

Классы источников под прямыми — исключены



Критерий общей энергетики

L = 5×10⁴⁴ erg/(Mpc³ yr) — совокупная светимость источников, необходимая чтобы получить наблюдаемый спектр КЛ (Auger, 2017)
Зависит от E_{min} внегалактических КЛ и соотношения L_γ/L_{CR}
Классы источников под прямыми — исключены



Alves Batista et al., 2019

Step two: realistic UHECR mock sets

Generate UHECR sets with state-of-art simulated skymaps

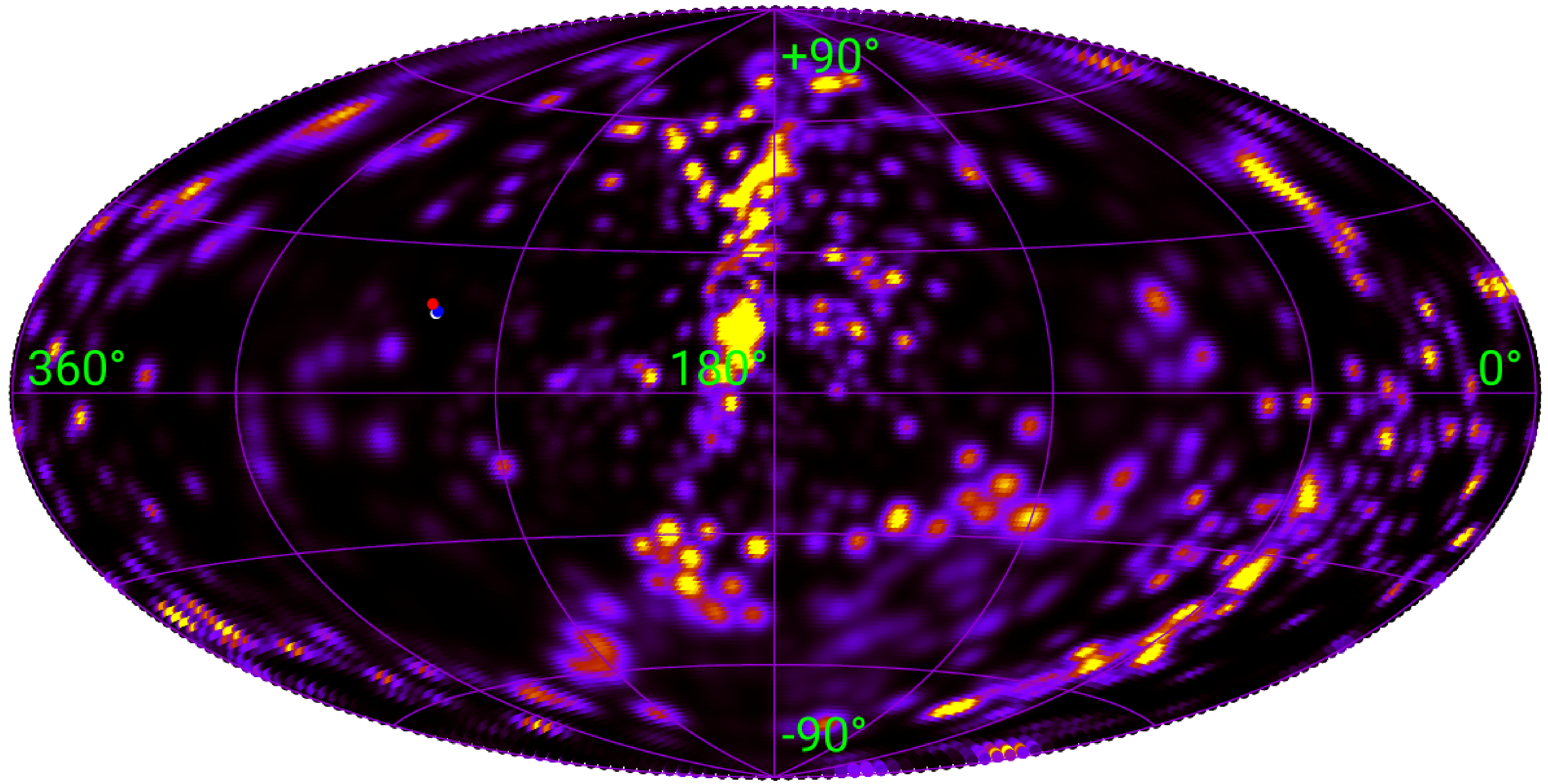
- Sources in LSS (corrected 2MRS catalog up to 250 Mpc, isotropy farther)
- Properly attenuated injected primaries (p-He-O-Si-Fe), secondaries for He & O are included (SimProp 2.4)
- Fix best fit injection spectrum separately for each primary (di Matteo & Tinyakov 2018)
- No EGMF deflections
- GMF deflections: backtracking for regular component,
- Non-uniform gaussian smearing for random component (Pshirkov et al. 2013)
- Sets are generated according to these maps with a spectrum adjusted to the observed one (TA@ICRC 2015)
- Effectively infinite statistics (statistical effects are reflected only in the data)
- **Only free parameters of the model are fractions of each primary**
- **All other uncertainties: to study separately (subominant!)**

Proton map at E = 100 EeV

Iron map at E = 100 EeV

Корреляция с источниками, протонный сценарий

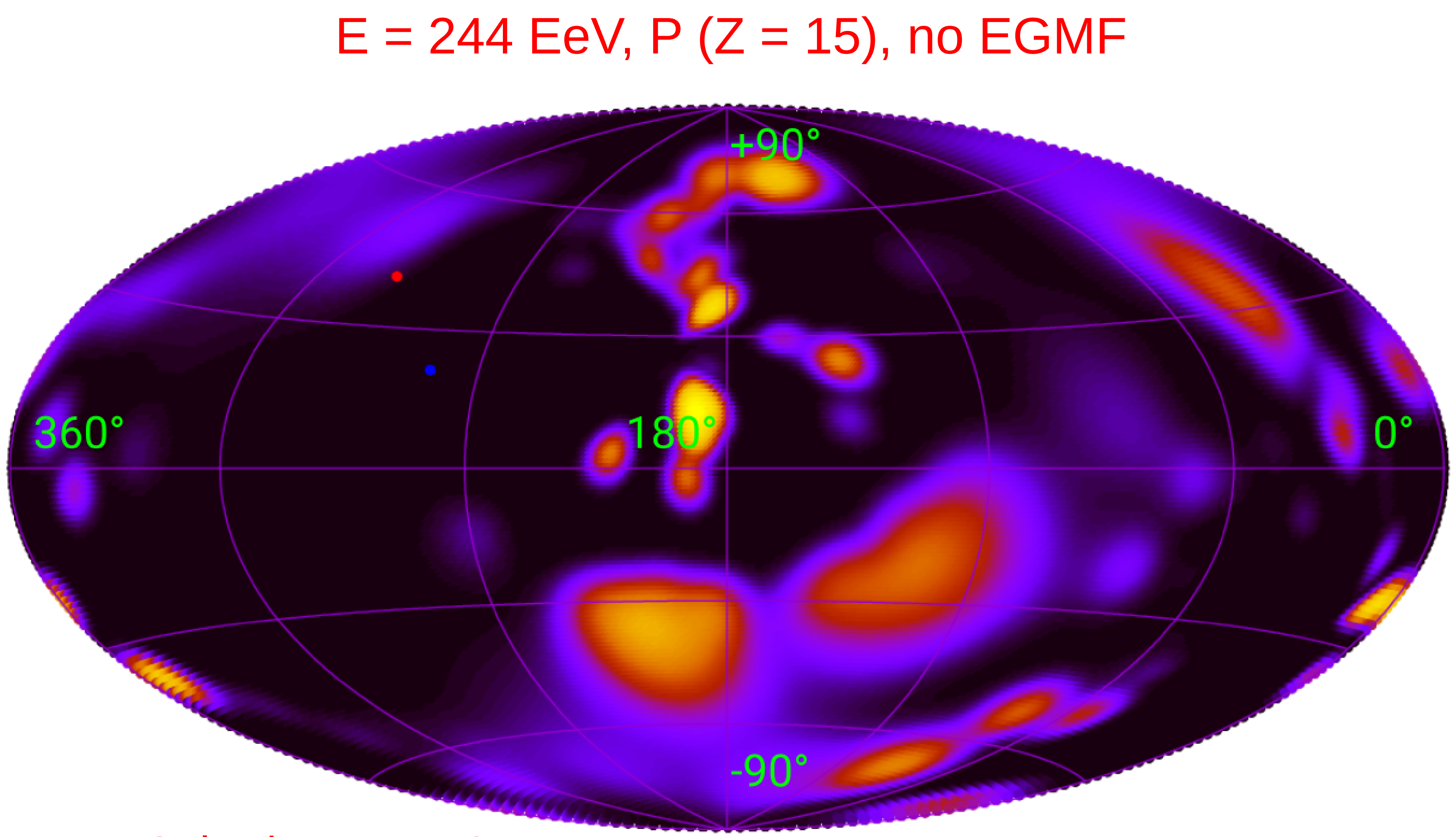
- Предположим что источник находится в какой-то галактике и он испускает протон
- Базовый сценарий: E = 244 ЭэВ, отклонение в галактическом магн. поле учтено, внегалактическое поле слабое
- Относительный ожидаемый поток с направления прихода частицы менее 1%→ базовый протонный сценарий маловероятен



Red dot: reg. Galactic MF JF’12
Blue: reg. Galactic MF PT’11

Корреляция с источниками, ядерный сценарий

- Предположим что источник испускает какое-то ядро
  - Из-за рассеяния на космическом фоновом излучении рождается каскад ядер с меньшим зарядом и протонов
  - Базовый сценарий: E = 244 ЭэВ, отклонение в галактическом магн. поле учтено, внегалактическое поле слабое
- Хотим поставить ограничения на корреляцию с 95% точностью:
  - Каков минимальный заряд излученного ядра чтобы относительный ожидаемый поток с направления прихода составлял хотя бы 5 %?



Red dot: reg. Galactic MF JF’12
Blue: reg. Galactic MF PT’11

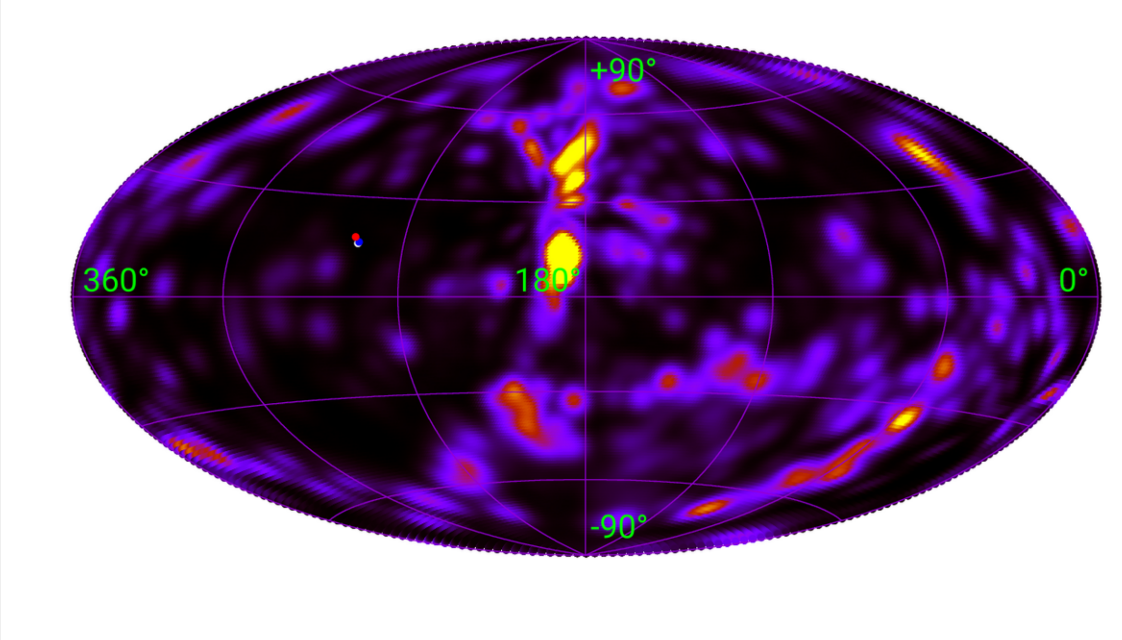
Correlation with sources, proton scenario: uncertainties

We can constrain the distance to the source by analyzing the CR propagation

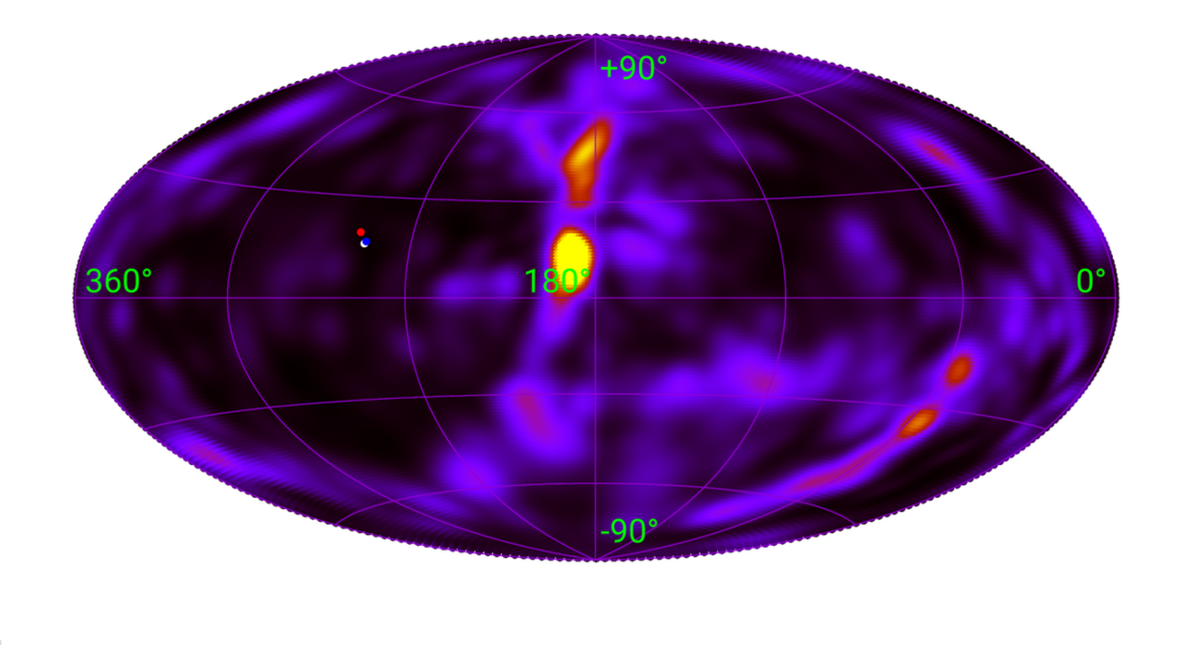
- Scenario Ia: E = 244 EeV, extreme EGMF
- Scenario Ib: E = $E_{detected}$ - 2σ (stat.) - (sys.) = 135 EeV, extreme EGMF

- The relative expected flux at the event direction is less than 1% in both cases → proton scenario is disfavored even with uncertainties! →
  - The event should be a nucleus!

- E = 244 EeV, EGMF



- E = 135 EeV, EGMF



Ограничения на концентрацию источников КЛ

Мы получили ограничение на расстояние до ближайшего источника: $D < 5.0^{+8.0}_{-0.0}\ \mathrm{Mpc}$

(нижней неопределенности нет из за ограничения каталога)

Хотим перевести это в универсальное ограничение на концентрацию источников КЛ: ρ

Считаем, что источники распределены во Вселенной вцелом случайно, по Пуассону

$$p(\rho, N) = \frac{e^{-\rho V}(\rho V)^N}{N!}$$

N — количество источников в объеме V

Чтобы получить ограничения на ρ на уровне 95% мы симулируем множество Пуассоновых реализаций 3D карты источников и требуем чтобы хотя бы один источник попадал в объем $V = 4/3\ \pi\ D^3$ по крайней мере в 5% реализаций

В базовом ядерном сценарии получаем D < 5.0 Mpc → ρ > 1.0 · 10^{-4} Мпк$^{-3}$

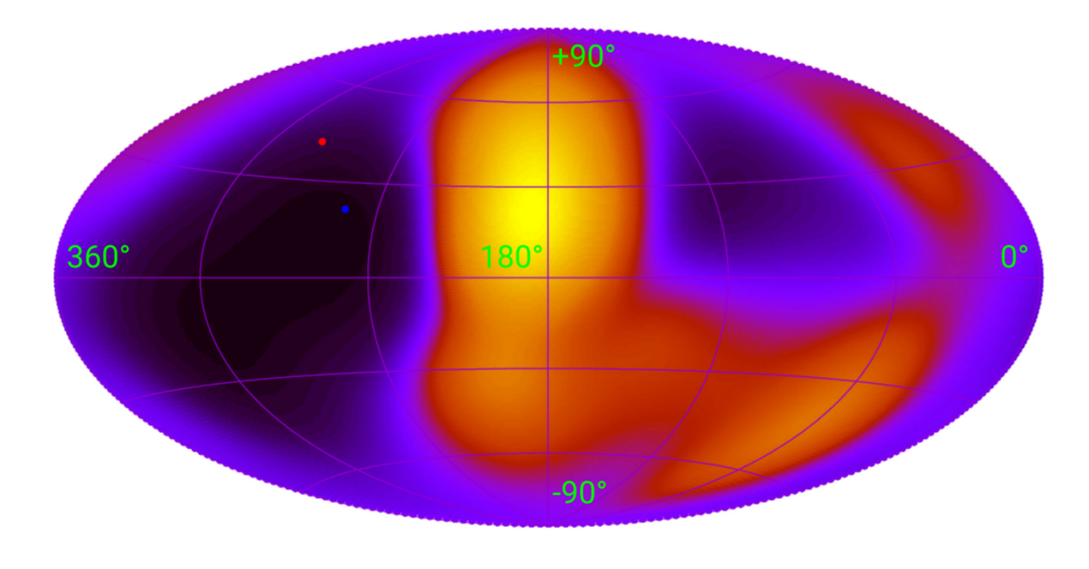
Correlation with sources, nucleus scenario: uncertainties

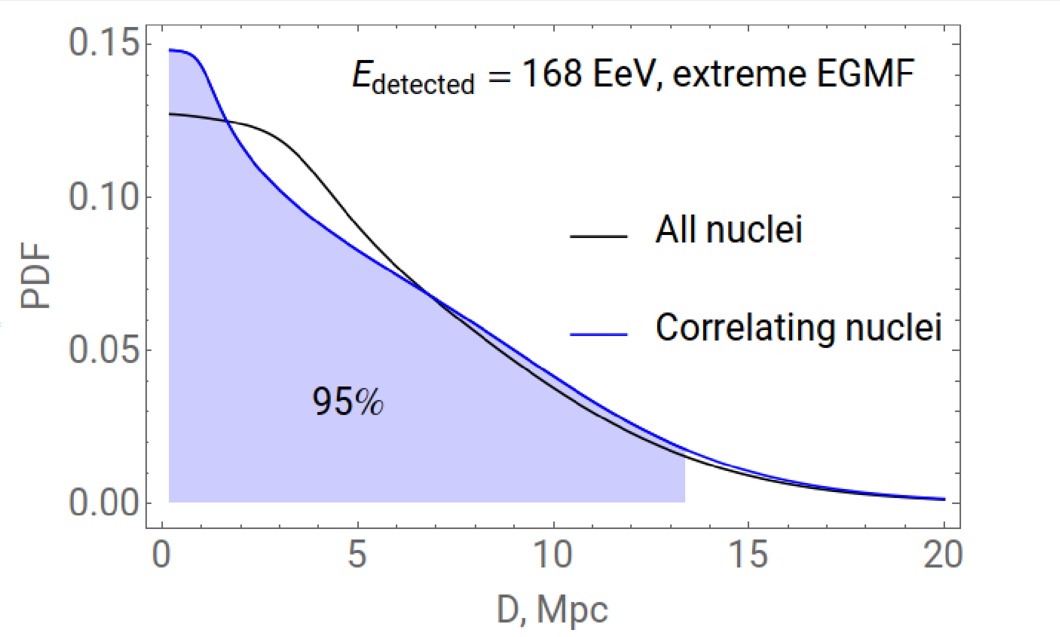
Take into account energy uncertainty and possible EGMF

For E = $E_{detected}$ - (sys.) = 168 EeV and with extreme EGMF the lightest correlated nucleus is S (Z=16)

Constrain the distance with the same procedure: D < 13.4 Mpc

- E = 168 EeV, S (Z = 16), extreme EGMF





Распространенность элементов в Солнечной Системе